Lake Champlain
Basin Program

PUBLICATION SERIES

Technical Report No. 20

Understanding Phosphorus Cycling, Transport and Storage in Stream Ecosystems as a Basis for Phosphorus Management

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for
Lake Champlain Management Conference

December 1996

THIS PROGRAM IS SPONSORED BY U.S.E.P.A. AND THE STATES OF NEW YORK AND VERMONT.

UNDERSTANDING PHOSPHORUS CYCLING, TRANSPORT AND STORAGE IN STREAM ECOSYSTEMS AS A BASIS FOR PHOSPHORUS MANAGEMENT

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This technical report is the twentieth in a series of reports prepared under the Lake Champlain Basin Program. Those in print are listed below.

Lake Champlain Basin Program Technical Reports

1. *A Research and Monitoring Agenda for Lake Champlain.* Proceedings of a Workshop, December 17-19, 1991, Burlington, VT. Lake Champlain Research Consortium. May, 1992.

2. *Design and Initial Implementation of a Comprehensive Agricultural Monitoring and Evaluation Network for the Lake Champlain Basin.* NY-VT Strategic Core Group. February, 1993.

3. (A) *GIS Management Plan for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc., and Associates in Rural Development. March, 1993.

   (B) *Handbook of GIS Standards and Procedures for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.

   © *GIS Data Inventory for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.

4. (A) *Lake Champlain Economic Database Project. Executive Summary.* Holmes & Associates. March 1993.

   (B) *Socio-Economic Profile, Database, and Description of the Tourism Economy for the Lake Champlain Basin.* Holmes & Associates. March 1993

   (B) *Socio-Economic Profile, Database, and Description of the Tourism Economy for the Lake Champlain Basin. Appendices.* Holmes & Associates. March 1993

   © *Potential Applications of Economic Instruments for Environmental Protection in the Lake Champlain Basin.* Anthony Artuso. March 1993.

   (D) *Conceptual Framework for Evaluation of Pollution Control Strategies and Water Quality Standards for Lake Champlain.* Anthony Artuso. March 1993.

5. *Lake Champlain Sediment Toxics Assessment Program. An Assessment of Sediment - Associated Contaminants in Lake Champlain - Phase 1.* Alan McIntosh, Editor, UVM School of Natural Resources. February 1994.

   Lake Champlain Sediment Toxics Assessment Program. An Assessment of Sediment - Associated Contaminants in Lake Champlain - Phase 1. Executive Summary. Alan McIntosh, Editor, UVM School of Natural Resources. February 1994.

6. *(A) Lake Champlain Nonpoint Source Pollution Assessment.* Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

   (B) Lake Champlain Nonpoint Source Pollution Assessment. Appendices A-J. Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

7. *Internal Phosphorus Loading Studies of St. Albans Bay. Executive Summary.* VT Dept of Environmental Conservation. March 1994.

(A) *Dynamic Mass Balance Model of Internal Phosphorus Loading in St. Albans Bay, Lake Champlain.* Eric Smeltzer, Neil Kamman, Karen Hyde and John C. Drake. March 1994.

(B) *History of Phosphorus Loading to St. Albans Bay, 1850 - 1990.* Karen Hyde, Neil Kamman and Eric Smeltzer. March 1994.

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8. *Lake Champlain Wetlands Acquisition Study.* Jon Binhammer, VT Nature Conservancy. June 1994.

9. *A Study of the Feasibility of Restoring Lake Sturgeon to Lake Champlain.* Deborah A. Moreau and Donna L. Parrish, VT Cooperative Fish & Wildlife Research Unit, University of Vermont. June 1994.

10. *Population Biology and Management of Lake Champlain Walleye.* Kathleen L. Newbrough, Donna L. Parrish, and Matthew G. Mitro, Fish & Wildlife Research Unit, University of Vermont. June 1994.

11. (A) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin. Executive Summary.* Yellow Wood Associates, Inc. January 1995.

(B) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin.* Yellow Wood Associates, Inc. January 1995.

© *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin. Appendices.* Yellow Wood Associates, Inc. January 1995.

12. (A) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program. Executive Summary.* Holmes & Associates and Anthony Artuso. March 1995

(B) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program.* Holmes & Associates and Anthony Artuso. March 1995

13. *Patterns of Harvest and Consumption of Lake Champlain Fish and Angler Awareness of Health Advisories.* Nancy A. Connelly and Barbara A. Knuth. September 1995.

14. (A) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program. Executive Summary - Part 2.* Holmes & Associates and Anthony Artuso. November 1995

(B) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program - Part 2.* Holmes & Associates and Anthony Artuso. November 1995

15. *Zebra Mussels and Their Impact on Historic Shipwrecks.* Lake Champlain Maritime Museum. January 1996.

16. *Background Technical Information for Opportunities for Action: An Evolving Plan for the Future of the Lake Champlain Basin.* Lake Champlain Basin Program. June 1996

17. (A) *Executive Summary. Economic Analysis of the Draft Final Plan for the Lake Champlain Management Conference.* Holmes & Associates and Anthony Artuso. July 1996

    (B) *Economic Analysis of the Draft Final Plan for the Lake Champlain Basin Management Conference.* Holmes & Associates and Anthony Artuso. July 1996

18. *Catalog of Digital Spatial Data for the Lake Champlain Basin* . Vermont Center for Geographic Information, Inc. September 1996.

19. *Hydrodynamic and Water Quality Modeling of Lake Champlain.* Applied Science Associates, Inc. July 1996.

20. *Understanding Phosphorus Cycling, Transport and Storage in Stream Ecosystems as a Basis for Phosphorus Management. Dr. James P.* Hoffmann, Dr. E. Allan Cassell, Dr. John C. Drake, Dr. Suzanne Levine, Mr. Donald W. Meals, Jr., Dr. Deane Wang. December 1996.

21. *Bioenergetics Modeling for Lake Trout and other Top Predators in Lake Champlain.* Dr. George W. LaBar and Dr. Donna L. Parrish. December 1996

22. *Characterization of On-Farm Phosphorus Budgets and Management in the Lake Champlain Basin.* Robert D. Allshouse, Everett D. Thomas, Charles J. Sniffen, Kristina Grimes, Carl Majewski - Miner Agricultural Research Institute. April 1997

This report was funded and prepared under the authority of the Lake Champlain Special Designation Act of 1990, P.L. 101-596, through the U.S. Environmental Protection Agency (EPA grant #EPA X 001840-01). Publication of this report does not signify that the contents necessarily reflect the views of the States of New York and Vermont, the Lake Champlain Basin Program, or the U.S. Environmental Protection Agency.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Phosphorus Cycling, Transport, and Storage in the LaPlatte River, Vermont

EXECUTIVE SUMMARY

This project was initiated in summer 1993 to provide fundamental scientific information on storage and transport of phosphorus (P) in streams in the Lake Champlain Basin to assist managers with decisions on long-term P reduction plans for Lake Champlain. Our study focused on the potential of a river to store and release P over time and on transformations in P form that may affect its biological significance. Principal objectives were: 1) to measure P storage in, and P cycling among water, sediment, periphyton, macrophytes, and detritus; 2) to assess P bioavailability; 3) to develop a simulation model to integrate observations on P transport, cycling and storage in various river compartments; and 4) to conduct P addition/attenuation studies in the river to collect empirical information on P dynamics and to assess model capabilities.

We used a conceptual framework in which we viewed streams as a series of linked reaches of different types. In each reach P can be stored in and cycled among biotic and abiotic compartments, controlled by varying physical, chemical and biological processes. Stream reaches were classified according to P concentration, substrate composition and flow regime. We hypothesized that substrate and flow were the most important factors determining actual processing of P within a reach. Because the same basic processes control P dynamics in all stream reaches, our study is an important step in developing a comprehensive description of P dynamics in a river.

We selected two 150 m reaches in the LaPlatte River that were subject to moderately high P loads. One (Spear Street site) was a cobble substrate, fast-flowing reach; the second (Bacon Drive site) was a deeper, soft-bottom pool reach. Both represent common stream environments in the Lake Champlain Basin. Seasonal stock assessments - estimates of the

quantities of P contained in the water, sediment, periphyton (attached microbial communities including epilithon and epiphytes) , rooted aquatic plants (macrophytes), and detritus (dead organic matter) - were obtained through intensive field sampling, with additional stock assessments conducted to evaluate the effect of a storm event on P storage. Flux rates between compartments were measured in laboratory adsorption/desorption and radiotracer experiments and in field experiments. Bioavailable phosphorus (BAP) was assessed using laboratory bioassays. Two P-addition experiments were conducted to study transport and attenuation under different physical/biological/flow conditions. Results of field and laboratory studies were incorporated into a dynamic simulation model that: 1) provided a quantitative tool to integrate the data collected; and 2) could eventually be developed into a management tool for predicting P dynamics in these and, potentially, other reaches under a variety of flow and P loading conditions. Future observations of additional reach types could be added to the data from this study to develop a more comprehensive understanding of a whole river system. Preliminary information on morphology of the whole river network was collected to aid in this process.

Results from the two studied reaches confirmed many of our initial ideas about stream reach function, but also provided some new insights into P dynamics in the LaPlatte River. Our classification of reach types on the basis of substrate, flow conditions and P concentration seemed to explain much of the observed variation of P in the river. Understanding the amount of this variation is an important first step in characterizing the river as a whole. The following bullets represent important insights gained from our research.

- **The two studied reaches behaved very differently with respect to P storage and cycling.**

The soft-bottom, slow-flowing pool environment of Bacon Dr. stored an average of 33.3 g/m^2 of P, ten times the average 2.8 g/m^2 stored in the cobble-dominated, fast-flowing stream at Spear St. While the majority of P was stored in sediments at both reaches, nearly all (97%) of the P was stored in sediments at Bacon Dr., compared to 80% sediment P at Spear St. P storage in living biomass was of a similar magnitude in the two reaches, but the types of biological communities fulfilling this storage function were distinctly different. Epilithon was a significant P stock at Spear St., averaging 19% of total stock, while epilithon never accounted for more than 1% of P in the Bacon Dr. reach. Macrophytes and epiphytes stored a negligible amount of P at Spear St., but stored as much as 3% of reach P at Bacon Dr. Clearly, substrate and flow conditions in the two reaches affected phosphorus stocks and storage potential.

- **Sediment represented by far the largest P reservoir in both reaches, ranging from 1.6 to 38 g P/m^2.**

The sediment compartment was defined as the amount of extractable P within the top 5 cm of sediments. Because this depth is critical in determining sediment P storage capacity, future work to determine how deep a sediment profile interacts with stream water P is needed to clarify this issue. Nevertheless, any reasonable assumption of how deep the sediment compartment should be (1 cm or greater), results in the conclusion that sediment is the dominant P reservoir in the river. Most of the sediment P present in the two reaches was in an HCl extractable fraction believed to be largely inert. However, 15% of the total was seemingly bioavailable (NaOH extractable P) and also active in adsorption-desorption processes. In laboratory studies, sediments were shown to be capable of rapid uptake of P from water, which is strongly dependent on the concentration of P in water.

- **Detritus did not represent a major stock or flux of P in either stream reach.** Many other studies of stream P dynamics have concluded that leaf detritus can be the dominant P reservoir. The lesser role of detritus in the LaPlatte is related to the largely open agricultural land use, in contrast to the forested streams examined in other studies.

- **Periphyton and macrophytes, where habitat was suitable, also represented a significant stock of P in both reaches.** At Spear St., where epilithon covered the rocky substrate, the stock of P in epilithon ranged from 0.1 - 1.1 g P/m^2. Epilithon was capable of rapid uptake of P from water (up to 100 mg P/m^2/day), particularly under the high P concentrations associated with moderately high flows. In contrast, at Bacon Dr. epilithon growth was minor while macrophytes and epiphytes were extensive, accounting for up to 1.4 g P/m^2. Laboratory studies showed that macrophytes took most of their P from water and that both macrophytes and epiphytes are capable of fairly high P uptake rates (19 and 55 mg P/m^2/day, respectively in late August at ambient P concentrations). These uptake rates increased several-fold in the presence of added P. Epilithon and epiphytes acquired P partly through active biological uptake and growth but also by trapping P-rich silt and clay particles in the gelatinous matrix around the algal cells. In some samples, epilithon was up to 90% inorganic matter by dry weight.

- **Epilithon and macrophytes play a major role in P cycling, despite the dominance of sediments in storing phosphorus.** Microcosm studies using radioactive P as a tracer showed that under typical streamwater P concentrations, biological uptake of dissolved P by epilithon, macrophytes, and associated epiphytes exceeded sediment uptake by a factor of 10. Field studies using an addition of concentrated P and Rhodamine WT dye to study P cycling in the stream during the dormant and growing seasons suggested that sediment may temporarily adsorb P as elevated concentrations of P pass over it. However, subsequent water low in P will cause desorption, resulting in a negligible net sediment uptake of P. During the growing season, with active biological uptake, longer term uptake resulted in a 30% reduction in P transport. Thus the biological component of the river appears to have the most important seasonal role in modifying P concentrations in stream water.

- **The bioavailability of P in streamwater varied dramatically over the seasons.** During the course of the study measures of TP, SRP and BAP varied both individually and in relation to each other. BAP concentrations were lowest in fall and greatest in summer, possibly due to the role of biological cycling of P in modifying P forms. In summer, BAP at the macrophyte-dominated reach was twice as high as at the lower biomass, epilithon-dominated reach. Observed BAP concentrations were from 5 to 100% of the SRP values. Not all the inputs of P to the lake will have the same immediate effect on lake processes, and in-stream P dynamics can have an important role in affecting bioavailability.

- **A moderate summer storm event resulted in only minor changes in total P storage.** Macrophyte stocks declined by about 30% at the soft-bottom Bacon Dr. site following the storm. Some movement of sediment was detected, although eroded sediment tended to be replaced by sediment from upstream, resulting in no net change in the sediment stock. Epilithon growth at the fast-flowing reach was stimulated by the high flow event, resulting in higher P uptake rates and slightly greater P storage. Our study was not designed to observe high flow events such as spring snowmelt or a 10-year storm. While these events clearly dominate annual P loading to the lake, the role of in-stream processes in reduction of high flow P transport is undoubtedly minor because spring runoff occurs in the dormant season and residence times in the stream are short during high flows. During the growing season, high flows can scour out epilithon, macrophytes and epiphytes and temporarily reduce P stocks. Transport and deposition of stream sediment is a function of terrestrial loading and instream scouring, which requires an entirely different experimental design to study. Despite these and other difficulties in studying high flow events, it is reasonable to conclude that typical high flow events, such as spring runoff and large summer storms, prevent in-stream processes of P storage and release from having any significant long-term role in reducing P loading to the lake. Gradually decreasing P concentration in the LaPlatte River following the Hinesburg sewage treatment plant upgrade suggests longer term, although still temporary, P storage in sediments.

- **P addition experiments suggested that P is not transported conservatively through a stream reach.**

  Phosphorus added to the stream was delayed by short-term (10-20 hours) retention even in winter. During the growing season, 30% of added P was retained beyond the time of the experiment (> 40 hours). Short-term retention was attributed to reversible absorption by sediments and biofilms, while long-term storage probably resulted from biotic uptake.

- **The dynamic simulation model developed in this study reasonably reflects P stocks and fluxes during the course of our investigation.**

  The dynamic simulation model, when based on reaches 150 m in length, reasonably predicted P stocks and fluxes within the two study reaches. Using the model to extrapolate to a larger river section, prediction of P retention and transport in the river following a pulse addition of P in winter approximated empirical observations. During the summer study, less retention of P in the river was predicted than observed; however, macrophyte-dominated, sediment-rich reaches were not included in the 3 km river section modeled. Extending our data on P stocks to the river as a whole using GIS descriptions of the LaPlatte River network, we estimate that about the same magnitude of P is stored in the stocks we measured in the river (8 Mg P, Mg = metric ton, see section 4.3) as is estimated to leave the river in a year (7.6 Mg P/yr). Modeling provides additional support to the idea that the river does not represent a long-term storage site for P.

- **In-stream processing in the LaPlatte River exerts only modest control over phosphorus loading to Lake Champlain.**

  Although modification of stream P concentrations within an event was demonstrated in our attenuation studies, significant modification of annual P loading from terrestrial sources probably cannot be maintained over a period of years. Observed changes in P stocks were small compared to estimated annual P input to the river from point and diffuse sources in the LaPlatte River watershed. Changes in river P concentration were minuscule over the span of each measured reach. Model simulations using observed conditions appear to adequately describe major transfers and transformations of P, and support the idea that long-term modification of P loads from terrestrial sources is not likely. The river's role in modifying the form of P is possibly more important than its role in changing total P transport. The observed seasonal changes in BAP and SRP may reflect biological activity. Although some of the P associated with sediment undoubtedly is buried after deposition in the lake, biologically available or released P adds to the P stock of the overlying lake water. Phosphorus associated with sediment may not immediately be available to promote algal growth, and thus may not pose as much of a water quality/eutrophication problem.

These observations are based on our view of the river during this study. Variation in river dynamics is much greater than that observed during the course of our study. In particular, extremely high flow events such as would be associated with 10-year or greater storms may create a very different set of observations. While the flux of P moving through the river system during storm events would undoubtedly be much greater than that observed during the course of this study, the implications for the mass balance of the river itself is unclear. Observations under these conditions in a large set of reach types would help to clarify the long-term role of sediment storage and erosion on P loading to Lake Champlain.

Our approach of idealizing the river into a series of linked reaches and using mass balances coupled with dynamic simulation models provided a useful framework for collecting data on river function. However, the current effort was designed as an initial step with study of additional reaches over a wider variety of flow conditions being essential to complete the conceptual and quantitative models.

Our study suggests that in-stream total P will ultimately reach the Lake; the rate of transport from source to lake can be expected to vary, but probably within the bounds of a year or less. Upstream distance alone is therefore not a good basis for targeting efforts to reduce tributary P loads to Lake Champlain. Stream environment and hydrologic regime are critical factors controlling P transport to Lake Champlain and may exert significant influence on P form and timing of delivery. We need to know more about in-stream processes, such as sediment and biotic interactions that were the dominant P fluxes documented in this study, the behavior of P in different reach types, and the effects of high flow events on P storage in order to more fully understand or apply such factors as management tools. Our model, which seemed to adequately represent fundamental principles controlling P transport dynamics, needs considerable refinement, but can still be highly useful as both a management tool and as a framework for evolving understanding P dynamics in streams.

For management purposes, limited resources available for P reduction might be most cost-effectively expended on keeping P out of the rivers, rather than counting on in-stream processes to keep P out of the lake. With respect to future river research, understanding of specific stream functions including transformations of P to available forms, uptake of P behind beaver dams, and P removal within riparian wetlands may contribute to the development of a comprehensive set of phosphorus management tools. Common sense management recommendations such as reduced P inputs, riparian area protection, stream bank stabilization and flood plain management, may provide the most efficient near term strategy for Basin-wide efforts.

INTRODUCTION

1.1 PURPOSE OF STUDY

Over recent decades, algal blooms resulting from high phosphorus (P) levels have impaired use of Lake Champlain, particularly for recreation. Existing P concentrations generally exceed the in-lake phosphorus criteria adopted in the 1993 Lake Champlain Water Quality Agreement (Lake Champlain Phosphorus Management Task Force 1993, VT DEC and NYS DEC 1994). Consequently, the Lake Champlain Management Conference has set a goal to reduce phosphorus inputs to Lake Champlain in order to promote a healthy and diverse ecosystem and provide for sustainable human use and enjoyment of the Lake (LCMC 1994).

Current management strategy for Lake Champlain calls for reduction of tributary P loads from both point and nonpoint sources. Cost-effective reduction efforts must be targeted carefully and managers must make difficult choices about which sources of P to address first with limited funds. The influence of P transport and storage processes in streams as P moves from a source to the Lake, and hence the importance of source distance from the Lake, is unknown. Once in a stream, does all P ultimately reach the Lake, making all P sources equally important to control, regardless of distance from the Lake? Is P retained in stream systems such that sources close to the Lake are most important to control? Do in-stream P transport processes impose a time lag between source reductions and downstream load reductions? Of course, this small project can not hope to fully answer all of these questions. Rather, the project sought to improve understanding of some of the fundamental processes influencing the behavior of phosphorus in streams.

The Eutrophication and Nonpoint Source Subcommittees of the Lake Champlain Basin Program Technical Advisory Committee (TAC) identified specific needs to improve understanding of the processes governing in-stream transport, transformation, cycling, storage, and release of P in streams in the Lake Champlain Basin. The purpose of this project, therefore, was to provide fundamental scientific information concerning the storage and transport factors affecting the downstream movement of P to support informed decisions in determining which sources of P should be targeted for treatment efforts.

1.2 GOALS AND OBJECTIVES

The overall goal of the project "Understanding Phosphorus Cycling, Transport and Storage in Stream Ecosystems as a Basis for Phosphorus Management" was to provide managers with a scientific framework to support implementation of long-term P reduction plans for the Lake Champlain Basin through improved understanding of P dynamics in stream systems. The project focused on the potential of stream reaches to store and release P over time and on transformations in P form that may affect the biological significance of the P load.

The specific objectives of the project were:

1) To measure P storage in, and P cycling among water, sediment, periphyton (the microbial community growing on surfaces in the stream), macrophyte, and detritus compartments in stream reaches typical of the Lake Champlain Basin;

2) To assess P bioavailability in typical stream reaches;

3) To develop an initial dynamic simulation model that describes P transport, cycling, and storage in a stream reach based on an understanding of P dynamics in typical stream reaches; and

4) To conduct P-addition studies in stream reaches to assess model capabilities.

1.3 CONCEPTUALIZATION OF THE SYSTEM

Streams may be viewed as complex ecosystems in which P storage, cycling, and transport is controlled by physical, chemical, and biological processes that vary widely in rate and that are often discontinuous over time. Downstream movement of P is subject to numerous uptake/release mechanisms and may be thought of as a spiraling process involving variable cycling, redistribution, and detention of soluble and particulate P forms coupled with continuous downstream flow (Elwood et al. 1983).

Hydrology is a critical driving force; flow energy and velocity control sediment particle size and load, bedload, rates of channel erosion or deposition, and outbank deposition in flood plains. Within the stream itself, P can be stored in and cycled among compartments, both biotic and abiotic. Periphyton can have very high P uptake rates, but community dynamics vary greatly with season, substrate, flow velocity, and ambient P concentrations. Sediments, both suspended and bottom, are often major reservoirs of P due to chemical sorption/desorption processes. Aquatic macrophytes may take up substantial quantities of P from either sediment or water; their growth and extent depend on substrate, flow, season, and light. Detritus contributes to in-stream processing of P through release and transport of plant tissue P during plant senescence and decomposition and by providing a substrate for biofilms with significant P uptake potential. While water may store relatively low amounts of P at any given time, downstream water movement is usually the dominant P flux through the stream system and P concentrations in water strongly influence chemical sorption/desorption equilibria and biological processes.

Phosphorus in a stream is stored in both biomass and sediments, but can be cycled and transformed by plant, animal, or bacterial growth, then released through excretion, leakage, or decomposition. Phosphorus is also simultaneously cycled into and out of sediments by adsorption/desorption and settling/resuspension. Some P may remain in sediments for months or years, but may also be released over much shorter periods due to biological activity or high flow events. Phosphorus moves downstream slowly when associated with bedload, more rapidly in suspended sediments or detritus or when dissolved in the water. Much of the P taken from stream water or sediments may accumulate in biomass during the growing season, but can be released during high flows or after the growing season. The net behavior of these competing phenomena is unknown.

1.4 THE STUDY FRAMEWORK

The operating hypothesis for this project was that the storage, cycling, and transport of P in stream ecosystems is fundamentally controlled by the physical environment of stream channel reaches and the level of P in the stream. Thus, stream environments may be classified on the basis of physical characteristics, e.g. a mountain stream or an impoundment, and by ambient P levels, e.g. a nutrient poor stream or a polluted, eutrophic stream. This framework is illustrated in Figure 1.1, where each cell represents a unique stream-reach ecosystem which stores, cycles, and transports P at different rates and amounts. An entire stream system may be composed of a unique series of stream reaches linked in a linear fashion. P introduced into the stream moves through this series of reaches before delivery to the lake. Thus, it is not just distance alone but also stream reach type that controls P transport.

While stream reach type and P level determine actual processing of P through a reach, the same basic processes control P dynamics in all stream reaches. Thus, the project selected two reaches representing common reach types in the Lake Champlain Basin and emphasized understanding of the processes of P storage and flux operating in these reaches. Our approach to quantifying these processes was to measure seasonal changes in

Physical Environment in the Stream Corridor

Phosphorus Levels	Mountain Stream	Babbling Brook	Lazy Meander	Impoundment
Eutrophic High P	**A** Steep, polluted stream	**D** Riffly, polluted stream	**G** Slow moving, polluted stream	**J** Impounded, polluted stream
Moderate P	**B** Steep stream in rural areas	**E** Riffly stream in rural areas	**H** Stream in rural flood plain valley	**K** Beaver Pond, small dam in rural area
Unimpacted Low P	**C** Wilderness Mtn Stream	**F** Wilderness Brook	**I** Wilderness meadows	**L** Wilderness Beaver Pond

Figure 1.1 Study framework: a two-dimensional array describing the relationship between the physical stream environment and phosphorus levels. The basis for this project is the hypothesis that P cycling, transport, and storage will differ among the cells or stream reach types. The same basic processes for cycling, transport, and storage of P operate in all compartments, but at different rates and magnitudes. The two stream reaches studied in this project represented environment types E (Spear St.) and H (Bacon Dr.).

stocks in the field and to estimate short-term P fluxes with radiotracers in laboratory microcosms.

Seasonal stock assessments - estimates of the quantities of P contained in the water, sediment, periphyton, macrophyte, and detritus compartments - were obtained through intensive field sampling over two years. Additional stock assessments were conducted to evaluate the influence of transient high flow events on P storage. Flux rates between compartments, e.g. sediment-water, macrophyte-sediment, were measured in laboratory adsorption/desorption and radiotracer experiments and in field experiments. Bioavailable phosphorus (BAP) was assessed using laboratory bioassays. Two P attenuation experiments were conducted in the study stream to evaluate transport and attenuation of a P addition under different physical/biological/flow conditions. Results of field and laboratory studies were incorporated into a dynamic simulation model that can be used to apply understanding gained in the project to other situations and to guide further study.

1.5 THE MODELING EFFORT

The simulation model describing the dynamics of P cycling, transport, and storage in stream reaches typical of the Lake Champlain Basin was the key mechanism used to integrate and apply the experimental results of the project. The overall model framework was established early in the project based on the project team's concepts of the stream ecosystem; the model structure also served to organize and guide data collection throughout the project. The stream reach was modeled as an open system, with P inputs entering the system and P outputs leaving the reach. At any instant in time, all the P in the stream reach was assumed to be located within five compartments (water, sediment, periphyton, macrophytes, and detritus) and the major physical, chemical, and biological processes operating within the reach to move and transport P among the compartments and through the reach were modeled. A schematic description of the conceptual model is shown in

Figure 1.2.

The model was developed within the object-oriented programming environment provided by STELLA II (Peterson and Richmond 1993). This modeling structure allowed the tracking of P dynamics in a stream reach by providing graphical and tabular outputs for a wide variety of variables. The main objective of the modeling effort was to allow simulation of P dynamics under conditions of constant or variable streamflow and P concentrations, during the growing and non-growing seasons, and over variable time periods. Required model features included ability to:

1. Compare P concentrations in streamflow entering the reach to P concentrations leaving the reach;
2. Compare input and output fluxes of P;
3. Track the dynamics of P storage within each of the compartments; and
4. Compare the P fluxes that transform and cycle P among the storage compartments.

The model serves to integrate the complex processes of P cycling within the stream system into an understandable and useful framework and provides the ability to apply the principles of that framework to other situations.

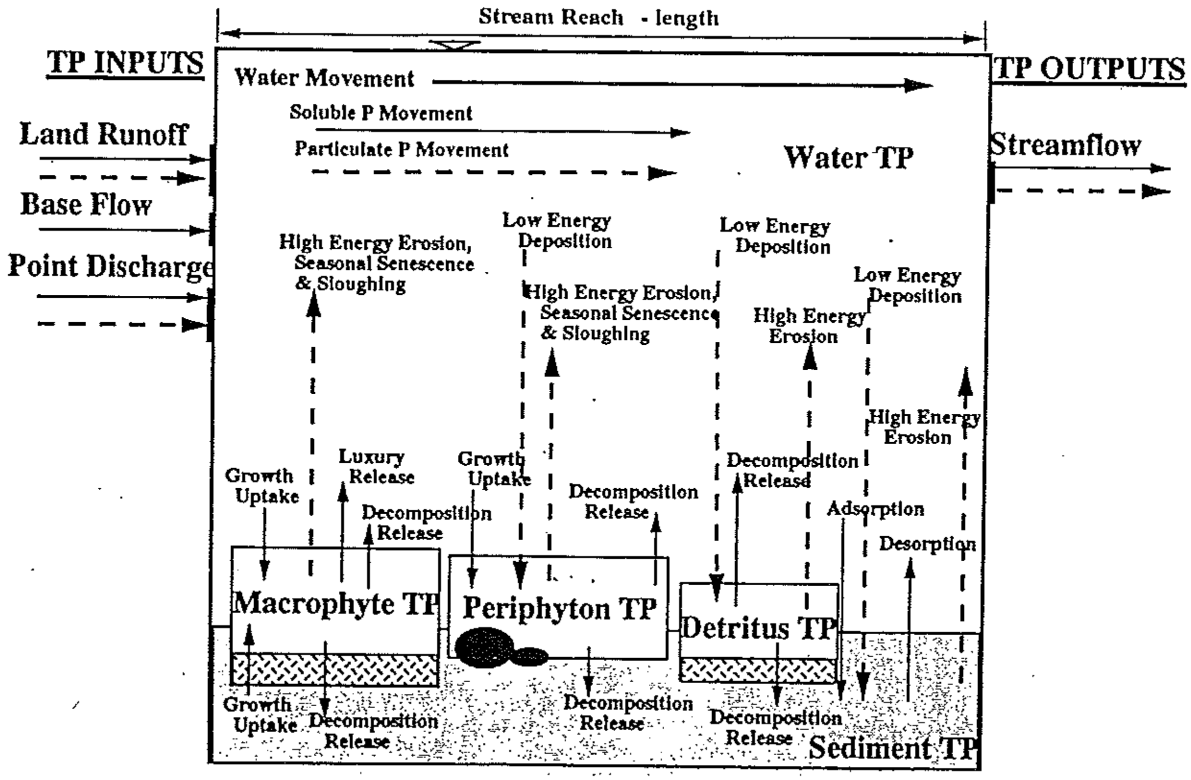


Figure 1.2 Schematic description of project conceptual model. The diagram divides the reach into five compartments (water, sediment, epilithon, macrophyte, and detritus) for storing TP in the reach and shows the various physical, chemical, and biological mechanisms functioning to move P from one compartment to another (vertical arrows) as well as water movement that transports TP through the reach (horizontal arrows). Solid and dashed arrows represent soluble and particulate fractions of TP, respectively. TP inputs to and outputs from the reach are also shown.

METHODS

2.1 SITE DESCRIPTION

This study was conducted in the LaPlatte River situated in northwestern Vermont (Figure 2.1). The river drains a total area of 13,815 ha (34,137 acres) and flows in a northwesterly direction from its headwaters in the forested foothills of the Green Mountains to Lake Champlain, a distance of approximately 24 km (40 miles). The forested headwaters region represents about 20% of the total area with the remainder in the mixed-agricultural Champlain Valley. The soils are a mixture of lacustrine sands, silts and clays, and glacial till. Agriculture, primarily dairy farming, accounts for about 47% of the land use in the watershed. Historically, the river has experienced heavy sediment and nutrient loads. Treated sewage from an historically overloaded waste water treatment plant located in the town of Hinesburg is discharged directly into the river at a point labelled in Figure 2.1. Table 2.1 lists the mean values for several water quality parameters reported in a ten-year monitoring program that ended in 1989 (Meals 1990). In 1992, the Hinesburg sewage treatment plant was upgraded to include tertiary treatment for phosphorus removal. Since then, phosphorus concentrations in the river have decreased to about 20% of previous levels (see Section 3.1.1).

Two 150 m study reaches, representing different physical environments, were selected on the main stem of the LaPlatte. The first site, designated the Bacon Drive site (Figure 2.1), was located about 6 km from the mouth of the river, just upstream of a USGS gaging station and represented physical environment type H from Figure 1.1, (p. 5). Over the course of this project, this site had a mean width and depth of 13.2 and 0.34 m, respectively. The substrate at this site was a diverse mixture of sand, silt and clay, with interspersed areas of pebbles and cobbles. Suitable substrate for epilithon (periphyton attached to rocks) represented about 35% of the total area of this reach. A macrophyte

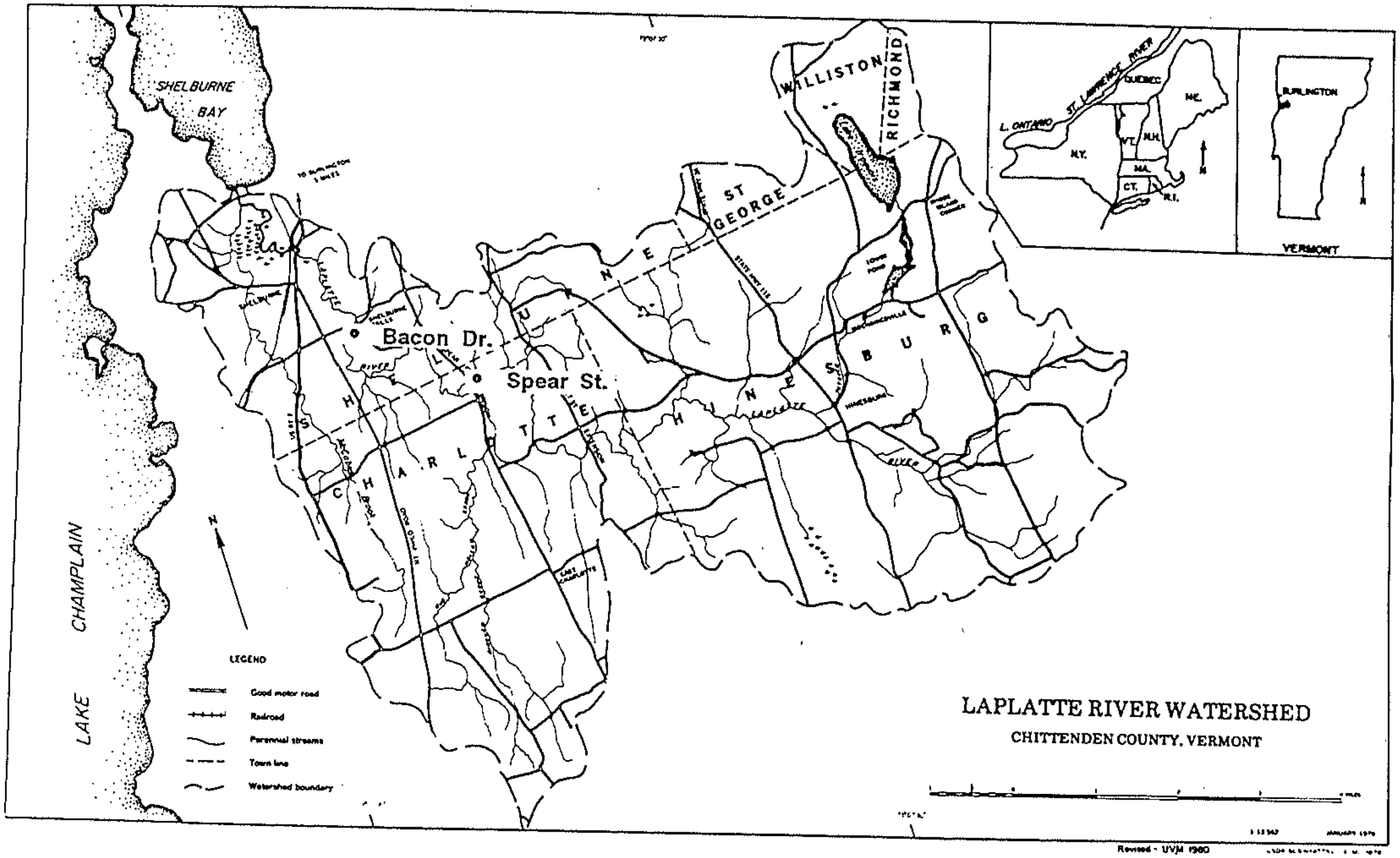


Figure 2.1 LaPlatte River watershed map indicating locations of study reaches.

Table 2.1 Water quality data for the LaPlatte River collected over the period from 1979 to 1988 at Spear St.site. Data represent the mean (± 1 SE) of the annual means reported in Meals (1990). Values are in mg/L.

PARAMETER	MEAN	SE
Total Suspended Solids	8.6	0.7
Volatile Suspended Solids	2.7	0.2
Total Phosphorus	0.42	0.06
Soluble Reactive Phosphorus	0.31	0.04
Particulate Phosphorus[a]	0.09	0.01
Total Kjeldahl Nitrogen	0.81	0.05
Ammonia Nitrogen	0.11	0.01
Organic Nitrogen[a]	0.65	0.04

[a] Calculated by difference.

community, dominated by *Elodea canadensis* Michx (Waterweed), and two species of Pondweed, *Potamogeton pectinatus* L. and *Potamogeton natans* L., covered approximately 75% of the reach by late summer.

The second site, designated the Spear Street site (Figure 2.1) and representing physical environment type E (Figure 1.1), was located about 10 km from the mouth of the river, and over the course of this study had a mean width and depth of 9.1 and 0.22 m, respectively. The substrate at this site was mostly cobble with interspersed boulders and small patches of a mixture of gravel, sand, silt and clay. Suitable substrate for epilithon represented about 75% of the total area of this reach. A sparse macrophyte community, dominated by the same genera as at Bacon Dr., covered less than 10% of the reach by late summer. Previous studies have shown that the fish community at this site was dominated by both *Rhinichthys atratulus*(Hermann) (Blacknose Dace) and *Rhinichthys cataractae* (Valenciennes) (Longnose Dace), and the dominant benthic macroinvertebrates were Chironomidae and Trichoptera, particularly caddisfly species of *Cheumatopsyche*, *Hydropsyche* and *Helicopsyche* genera (Meals 1990). Photographs of the Bacon Dr. and Spear St. sites are shown in Figures 2.2 and 2.3.

Streamflow in the LaPlatte River over the period of study was generally within the normal historical range (USGS 1995, Meals 1990). Mean daily discharge over the two year study period at the Shelburne Falls USGS station just downstream of the Bacon Dr. site is plotted in Figure 2.4. Average annual discharge was 39.2 ft^3/sec (0.11 m^3/sec) and 40.7 ft^3 (0.12 m^3/sec) for water years 1993 and 1994, respectively, compared to mean annual discharge over the 1990 - 1994 period of record for that station of 42.3 ft^3 (0.12 m^3/sec). Mean annual discharge recorded at the Spear St. station from 1979 to 1989 (Meals 1990) ranged from 17 to 39 ft^3/sec (0.05 to 0.11 m^3/sec); note that the Spear St. location drains just

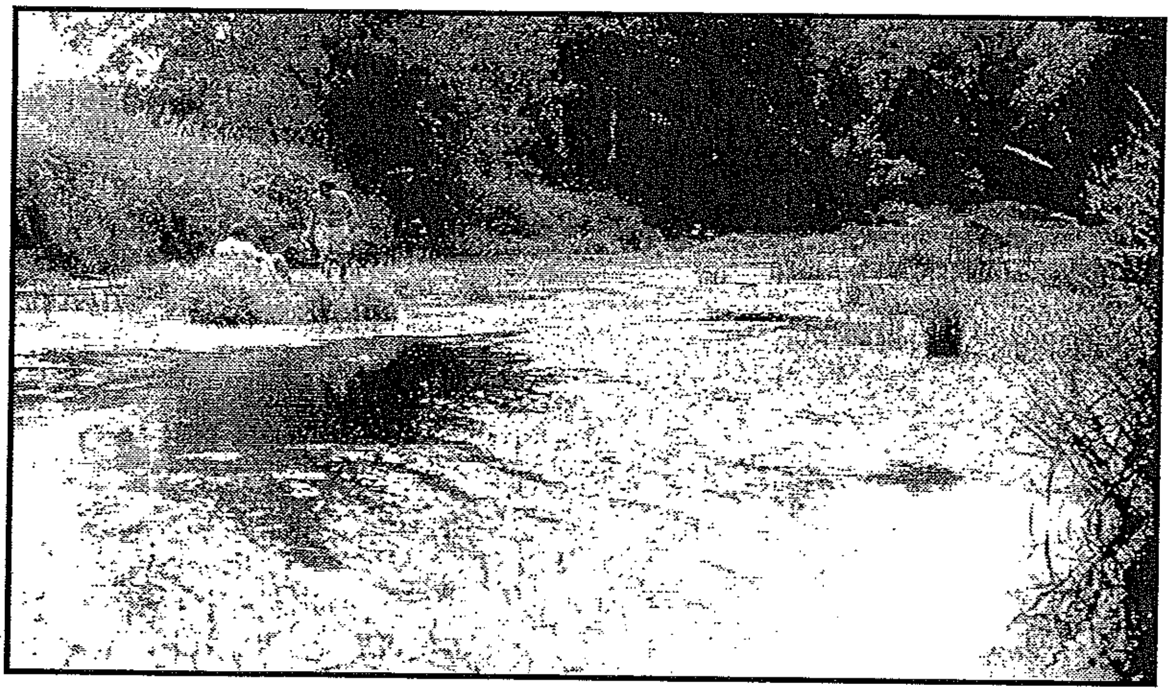


Figure 2.2 Photograph of the Bacon Dr. site.

Figure 2.3 Photograph of the Spear St. site.

66% of the area of the USGS station. The highest mean daily discharge recorded at the USGS gage over the period of study was 426 ft^3/sec (1.21 m^3/sec) in April, 1994, a value fairly typical of values observed at Spear St. in the 1980s (Meals 1990). Note that the stock assessments and attenuation experiments indicated in Figure 2.4 were conducted at fairly low flow conditions due to safety issues and other limitations on working in the stream under higher discharge conditions.

2.2 STOCK ASSESSMENT

2.2.1 Field Methods

The various compartments (water, sediment, epilithon, macrophytes and detritus) were periodically sampled from August, 1993 through April, 1995. Sampling of all compartments was generally completed within a week so that results would represent comparable stream conditions. In many instances sampling of all compartments was conducted simultaneously, moving from the downstream end of each reach towards the upstream end in order to minimize the effects of sampling on subsequent sites. The two reaches originally selected for study, and which were sampled in August, 1993, were at Bacon Dr. and at Carpenter Rd. Subsequent to this sampling, however, construction of a beaver dam at the Carpenter Rd. reach sufficiently altered the hydrology of the reach to mandate a relocation to the subsequent Spear St. site. In addition to the seasonal samples, each compartment was sampled before and after a storm in August, 1994.

2.2.1.1 Water

Grab samples of water were collected at the upper and lower ends of each reach. For each stock assessment, water samples were collected prior to sampling other compartments to avoid the effects of stream bed disturbances on P concentrations in water; downstream samples were always collected before upstream samples for the same reason.

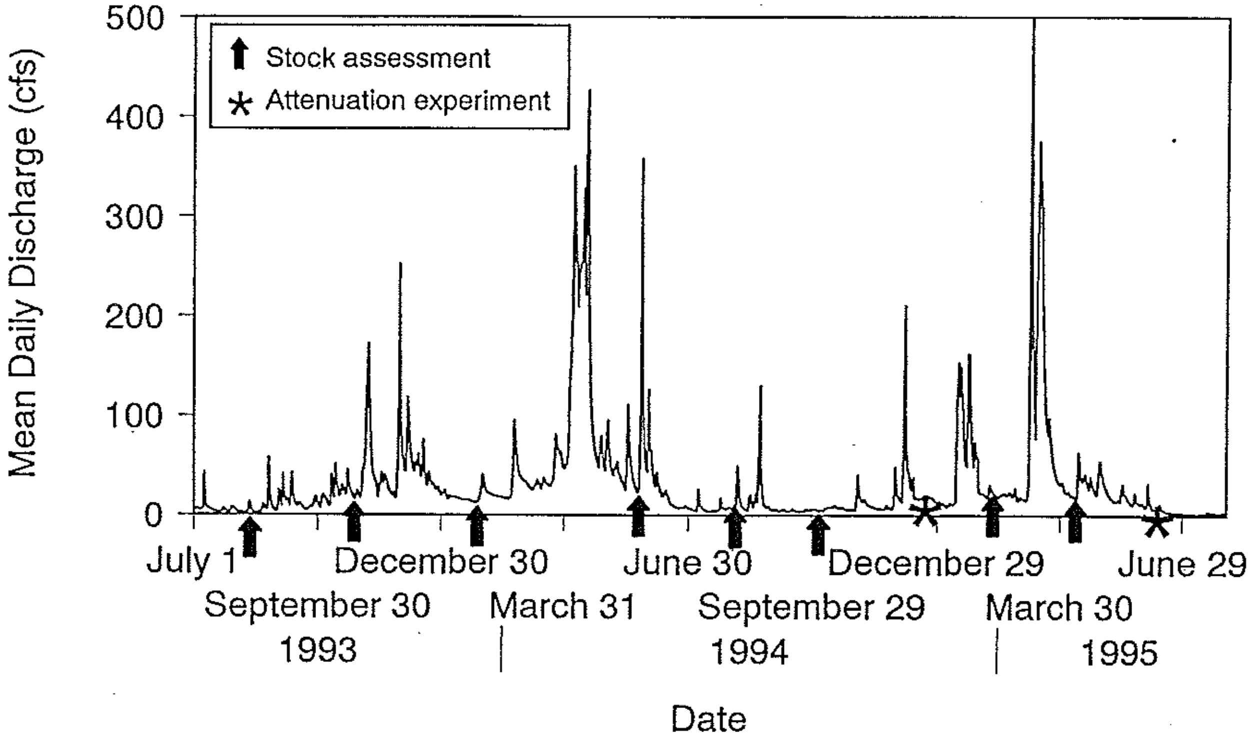


Figure 2.4 Mean daily discharge, LaPlatte River at Shelburne Falls, July 1, 1993 - July 31, 1995. Times of seasonal stock assessments and attenuation experiments are indicated.

At each location, samples were collected from just under the water surface at two locations across the width using acid-washed, polyethylene bottles. Sampling points were selected to be in the main flow of the stream. For the first stock assessment (8/93), six samples were collected across each stream transect in order to assess horizontal variability. Because no significant differences were observed among these six samples for any transect, only two samples were collected from each transect on subsequent assessments. A field duplicate sample was collected from either the upstream or downstream transect at each reach during each stock assessment. Samples were immediately placed on ice and transported to the laboratory within two hours of collection.

2.2.1.2 Sediment

In order to serve as a location reference base for sediment stock assessment, base maps were prepared for each stream reach. The Bacon Dr. reach was mapped by pace and compass tied to surveyed reference points at a scale of 1:200. The Spear St. site was mapped in 1993 by Hemenway and Tolley (1993) at a scale of 1:300. A transect line, approximately 25 m upstream from the lower end of the reach, was established before the May, 1994 sampling. Four specific sites were located along this transect from which sediments were collected each sampling time.

In July 1993, sediment texture within the Bacon Dr. reach was mapped by examining the sediments along 16 transects (one every 10 m). The sediment texture at this site was visually classified every meter along each transect. Two transects were added to the Bacon Dr. site the following year. The first, along which there were five specific sampling locations, was added just prior to the May 1994 sampling and was located approximately 28 m upstream from the lower end of the reach; the second was added prior to the August 1994 sampling and was approximately 64 m upstream from the lower reach boundary. Three sediment sampling sites were located along it. These additional transects and sampling locations were established so that sediment samples could be retrieved at different times from approximately the same locations thus minimizing areal variability when making temporal comparisons.

The sediment texture at Bacon Dr. ranges from fine grained silts and clays to coarse sand, pebbles and some cobbles, and coring was the preferred sampling procedure. Undisturbed core samples of up to 20 cm were taken using a hand-held coring apparatus (4.7 cm diameter). Twenty four sediment locations were selected using a stratified random sampling methodology for the August 1993 and November 1993 stock assessments. This method was chosen because the data from the sediment texture characterization showed five different sediment types: 1) coarse material consisting of a gravel matrix plus sands, silts and clays; 2) coarse sand matrix; 3) medium sand matrix; 4) silt plus fine sand matrix and 5) clay matrix. Equal numbers of samples were randomly collected from each sediment type. Because the various sediment types did not remain constant in areal distribution, the stratified random sampling methodology was abandoned after the November 1993 stock assessment. The February 1994 sampling sites were randomly located with both sediment and epilithon being sampled at the same locations. Sediment was collected at twenty of the randomly selected locations. For the subsequent sampling dates, the locations were selected randomly , but not stratified.

Scour chains were placed in the stream channel in the summer of 1994 to monitor sediment movement. Each chain set consisted of two with a half centimeter scale posts tied together with a one meter chain. Large rings were attached to either end of the chain to allow the chain to move freely on the posts. One chain was placed perpendicular to stream flow and the other was placed parallel to the stream flow. When installed, the rings were placed at the sediment surface and the location on each post was recorded to the nearest 0.5 cm.. After each high flow event, the chains were checked. Erosion caused the rings to slide down the posts to a new level, whereas with deposition the rings and chain were covered with sediment. The results were noted and the chains were reset. Four events were monitored during the summer of 1994 before macrophyte growth made it impossible to place the chains in a clear channel location. The last event corresponds to the pre- and post-storm sampling event of August 1994.

Sediments at the Spear St. site consisted mostly of pebbles, cobbles, and boulders with fine grained sediments (sands, silts and clays) located in interstices and in pockets behind large rocks. Twenty-four sample locations were randomly selected for each sampling time. Because of the armored nature of this reach, coring was not feasible. Therefore, bulk grab samples were taken from the interstices between coarser (pebble, cobble, boulder) material by scooping this material into precleaned, precapped, core barrels to minimize the loss of fine material. To quantify the area of interstitial fine grained sediments versus cobble/boulder armored stream bottom, 50 random locations were point counted. The point count consisted of identifying stream bottom substrate as "fine grained interstitial" or "boulder/cobble" at 10 cm intervals (100 points) within a 1 m^2 frame.

2.2.1.3 Epilithon

Both sites were sampled once each season from Summer 1993 to Spring 1995. Additional sampling occurred on two occasions: (1) in August 1994, following a storm that had occurred 5 days after the routine summer sampling; and (2) in June 1995 before and after the experimental release of a phosphorus pulse (~ 1 kg P) to the river that was part of a P attenuation study (see Section 2.8.). Prior to epilithon sampling, temperature, pH and conductivity were measured and water samples for bioavailable P (and on one occasion nitrate-nitrogen and total Kjeldahl nitrogen) were collected from both the upstream and downstream boundaries of the study reaches. At each sampling, 20 random coordinates were established at each site to determine sample locations. At each location, sample depth and river width were recorded for estimating cross sectional area. Epilithon was sampled from each location if suitable substrate (i.e. rock surfaces) were present. The proportion of the 20 locations that yielded samples was used to estimate the percentage of the reach supporting epilithon. Sampling involved scraping and brushing the epilithon from a measured area ($x = 20.2 \pm 1.2$ cm^2; 1SE) on the chosen rock into acid-cleaned polypropylene cups.

2.2.1.4 Macrophytes and Epiphytes

To assess the phosphorus stock in macrophytes at the two study reaches, plants were collected, weighed and analyzed for phosphorus content seasonally between Summer 1993 and Spring 1995 (plants were not collected at Spear St. in summer 1993). A random sampling design was used at the Spear St. site, where plants were sparse, with 0.1 m^2 quadrat sample numbers varying from a low of 8 in winter to 40 during summer and fall of 1994 (Table 3.9). At the Bacon Dr. reach, random quadrat sampling (8-40 sites) was undertaken during those seasons when plant growth was low (in winter and spring of both 1994 and 1995, and in the fall of 1994), but a stratified random sampling design was followed when plants were abundant but distributed in patches.

In the summer of 1993, the strata were classified visually as "very dense" (>75% coverage per unit area), "dense" (50-75% coverage), "sparse" (25-50% coverage), and "open" (0-25% coverage). In the fall of that year, when pondweed stocks had dwindled, only two strata were used, "elodea bed" and the "open channel." In the summer of 1994 the strata were defined differently: "dense," was defined as >66% coverage, "sparse" as 33-66% coverage and "open" as 0-33% coverage. Sampling points within each of the strata were selected randomly by numbering grid cells on a map of the reach and generating random numbers to obtain sample locations within each stratum.

Samples of macrophytes were collected by manually uprooting all the stems from within each 0.1 m^2 quadrat. The plants were rinsed free of loosely attached epiphytes by gently waving them in the streamwater. They were then placed in plastic bags and transported to the lab in a cooler with ice.

Epiphyte areal standing stock was estimated as the product of average epiphyte biomass on a gram of plant material (measured only at the Bacon Dr. reach, as plants were scarce at Spear St.), and the mean plant biomass per m^2 in a reach. In the summer of 1993, epiphytes were collected by placing a nitex mesh plankton net around a single plant stem, waving it in the stream water to detach epiphytes, and rinsing the epiphytes from the net into an attached bottle.

In the summer of 1994, epiphytes from plants in the Bacon Dr. reach were collected differently. The end of a single plant stem was gently placed into a 250 ml bottle, and clipped from the rest of the stem. The bottle was filled with stream water and capped for transport to the lab.

In addition to the regular seasonal samplings, samples were collected following a high flow event during the summer of 1994, and during the period of macrophyte senescence at Bacon Dr. (late September).

2.2.1.5 Detritus

Sampling methods for detritus, as for other stocks, had to be adjusted according to the specific conditions of each sampling time, and for the types of detritus collected. When the LaPlatte River was free of ice, estimates of detrital mass on the channel bottom of the stream reaches were obtained through random sampling of 40 quadrats (0.1 m^2), except for in the Summer 1994 when 25 quadrats (0.5 m^2) were sampled. Quadrat sampling was supplemented with transect-based assessment of wood mass. The material hand picked from within the quadrats included leaves, twigs, fragments of dead macrophytes and occasional invertebrate carcasses. Due to the limitations of handpicking, only objects >1cm in length (commonly referred to as coarse particulate matter, CPOM) were collected. Dead leaves still attached to live plants were not included in the CPOM estimate, but were included in estimates of plant biomass.

Wood present as logs and branches >2 cm in circumference was not included in the estimate of CPOM, due to the large variance that would result from including these large-massed pieces. Instead, wood mass was estimated by running ten one-meter wide transects across each stream reach and measuring the dimensions of every piece of wood enclosed by the transects. Samples of premeasured wood were returned to the laboratory for drying and weighing, thus facilitating calculation of wood density, a variable necessary for the calculation of wood mass from wood volume.

During winter samplings, transects could not be established because of ice cover. Difficulties in augering through several feet of ice cover also required the reduction of the number of quadrats samples for CPOM (15 at the Spear St. reach, and 8 at the Bacon Drive reach) and the reduction of the area of these quadrats to 0.2 m^2 (the area of the augered holes). Retrieval of detritus through the augered holes was not as efficient as detritus retrieval from open water. Sampling through the ice required the sampler to identify detritus on the stream bottom by feel (through an insulated glove) and then, using a flashlight, examine the bottom for unretrieved material. We therefore believe that winter detrital material may have been underestimated. CPOM samples collected for analysis were kept in a cooler on ice before being returned to the laboratory for oven drying and weighing.

Some of the detritus in the LaPlatte River was present on the water surface or in suspension travelling downstream. The flux of detritus moving downstream during the seasonal stock assessments was measured using a trapping technique. In Spring 1994, the detritus trap was simply a screen (1 mm^2 mesh) positioned across a portion of the stream. Thereafter, a more complex trap was used in order to determine the size distribution of the detrital material. It consisted of a cubical frame with three wire mesh screens. The screens were positioned about 30 cm apart, and facing into the stream flow, so that detritus was strained through them. Water flowed first through the coarse-mesh screen (1.68 cm^2), then through a medium-mesh screen (0.30 cm^2) and finally through a fine-mesh screen (1 mm^2). This arrangement allowed for an assessment of the suspended detritus particle size as well as an assessment of the total suspended load.

The trap was placed in the water for about two hours, then removed. The detritus caught on each screen was picked off, dried and weighed, and subsamples analyzed for P content. Water velocity and depth at the trap location were recorded to allow calculation of the volume of water that had passed through the trap.

2.2.1.6 Landscape-Scale Evaluation of Stream Surface Area

Some approximation of the total stream bottom surface area was desired in order to put the reach scale studies into a broader perspective. Using USGS single-line GIS data digitized from 1988 1:20,000 orthophotographs for Chittenden County, a rough estimate of the linear extent of the LaPlatte River surface water network was calculated. The main limitation of this dataset is that only a partial representation of first order streams is possible (Strahler method of assigning order). First order streams are the most difficult to capture in such a GIS format because 1) the concept of what constitutes a first order stream is not fixed, 2) the current common resolution of orthophotographs limits measurement to about

0.5 m, and 3) many first and second order stream features are obscured by covering vegetation. Average stream width for greater than second order streams was taken off of the orthophotographs using randomly selected stream cross-sections. For first and second order streams, widths were measured in the field at road/stream intersections for eight randomly selected streams.

Stream surface area was estimated by multiplying length X width for each stream section (arc) in the database. This yields an estimate of the water surface at the time of the width evaluation. Winter and summer surface areas would differ by large amounts. This evaluation is probably best referenced to mid-flows. Extrapolating water surface area to sediment area would require measurement of stream cross-sections. This was not done. However, water surface area is directly applicable to the quadrat areas used in this study to measure stocks of periphyton, sediment, macrophytes, etc.

2.2.2 Laboratory Analyses

2.2.2.1 Water

Immediately upon receipt in the laboratory, water samples were prepared for SRP analysis by filtering an aliquot through a 0.45 μm membrane filter. The filtrate was stored at 4°C in acid-washed polyethylene bottles until analysis. Samples to be analyzed for TDP were acidified with concentrated H_2SO_4 to pH <2 following filtration and stored in acid-washed polyethylene bottles at 4°C. Samples for TP analysis were acidified without filtration and stored in acid-washed polyethylene bottles at 4°C until analysis.

Phosphorus analyses for SRP, TDP and TP were conducted using accepted methods, within recommended holding times , i.e. 48 hours for SRP and 28 days for TDP and TP (USEPA 1983). Water samples from stock assessments early in the project were sent to the

Vermont Department of Environmental Conservation laboratory in Waterbury, VT, where samples were analyzed for TP and/or TDP in an autoanalyzer (Technicon Auto Analyzer II) after persulfate digestion according to EPA method 365.4 (USEPA 1983). Beginning with May 1994 stock assessment, TP and TDP analyses were conducted in the University of Vermont, School of Natural Resources water resources laboratory using either a Technicon Auto Analyzer II or a Shimadzu UV160U spectrophotometer depending upon the number of samples in a particular batch. Analytical chemistry was the same in either case, and the results are comparable.

2.2.2.2 Sediments

All sediment samples were analyzed for total phosphorus using a combination of ignition followed by hot HNO_3-H_2SO_4 digestion and spectrophotometric analysis according to EPA 365.2 . This procedure is a modification of the digestion for TP in water as presented in Standard Methods (APHA 1989). A minimum of ten percent of the bottom sediment samples from each reach were analyzed for NaOH phosphorus, HCl phosphorus and grain size (percent gravel, percent sand, and percent silt+clay). The NaOH and HCl extractions followed the procedures outlined by Hieltjes and Lijklema (1980) with one exception. Instead of sequential analysis, duplicate samples were used, and the digestions were followed by spectrophotometric analysis according to EPA method 365.2. Sediment grain size was obtained by sieving for gravels (> 2 mm), sands (2 mm - 0.063 mm) and silts plus clays (< 0.063 mm). Sand and silt+clay fractions were analyzed for total phosphorus. To monitor laboratory procedures, sediment standards, phosphorus standards, blanks and sample replicates were analyzed.

The randomly collected core samples from the Bacon Dr. site were first cut into three depth intervals, 0-2 cm, 2-5 cm, and 5-10 cm. Each interval was weighed to obtain a total wet sample weight. All interval samples were homogenized, and subsampled for TP analysis and percent water. The dried samples were sieved to separate out particles larger than 2 mm. Between 0.2 g and 0.4 g of the < 2 mm fractions were subsampled for combustion prior to the hot HNO_3-H_2SO_4 digestion. Ashed sediment samples were placed in 100 ml Erlenmeyer flasks, filled with 50 g of distilled water . To this, 2 ml of concentrated H_2SO_4 and 10 ml of concentrated HNO_3 were added. Boiling chips were added and the samples were digested on hot plates until the volume was reduced to under 10 ml. The samples were allowed to cool, then were filtered through glass fiber 1 μm (nominal) filters to remove the particulate material. The pH was adjusted to 7 with NaOH and H_2SO_4 using a phenolphthalein indicator. Dilutions were made as necessary to bring P concentrations into the working range of standards (0.01 mg/L to 1.5 mg/L). The combined reagent was added, and the samples, replicates, blanks and standards were analyzed on the spectrophotometer.

Transect cores were cut into four intervals, 0-1 cm, 1-2 cm, 2-5 cm, and 5-10 cm. Each interval was weighed to get a total wet sample weight. All transect samples analyzed were wet-sieved with distilled water through a 2 mm and then 63 μm sieve. The silts+clays in suspension were collected in a graduated cylinder. The gravel and sand fractions were rinsed into pre-weighed beakers and dried. The silt+clay fraction in an aqueous suspension was homogenized, subsampled by pipette, and the sediment slurry filtered onto four prewashed, pre-weighed 1μm (nominal) filters. The filters plus sediment were dried in a desiccator. The dried sand and silt+clay fractions were weighed then combusted using the same methods as previously described. Three of the four filters plus sediment were aggregated for total-P analysis.

The NaOH and HCl extractions were not done sequentially, but rather on replicate samples. The extractions were done on wet sediment taken from each core and interval analyzed. At the same time, a duplicate sample was taken, weighed and dried for percent water and TP analysis. The NaOH and HCl extractions were done following the procedures outlined by Hieltjes and Lijklema (1980), followed by spectrophotometric analysis according to EPA methods. The subsample dried for TP analysis was analyzed using the procedures as described above.

Because Spear St. samples were bulk grab samples rather than cores, they were not subsectioned by depth but rather were split into gravel, sand, and silt+ clay fractions using the methods described for the Bacon Dr. transect samples, with sand and silts+clays being analyzed separately. Particles larger than sand have not been analyzed because it was assumed that: a) they would contain little phosphorus, and b) what phosphorus that was associated with the larger particles was probably present as epilithon. Nevertheless, the mass of the gravel and larger component has been included in calculating the mass of P per m^2 of total sediment. Analyses for TP, NaOH-P, and HCl-P were performed on the sand and silt+clay fractions following the above mentioned methodologies. Combustion or Loss on Ignition (LOI) consisted of ashing the sediment samples at 450° C for a minimum of three hours. This procedure falls within the guide lines presented in Ackerly (1983).

Data are presented as concentrations (mg P/ g dry sediment), as mass per unit volume (mg P/ cm^3), and as mass per unit area to an assumed depth (mg P/m^2) assuming depths of 0-2 cm and 2-5 cm.

2.2.2.3 Epilithon

Epilithon dry weights were determined by evaporating the samples to dryness (85° C) in tared crucibles and weighing to $\pm$0.1 mg. The accumulation of epilithon on the nutrient-diffusing substrates was determined by scraping and brushing the epilithon from a circular area (22.1 cm^2) on the top of each saucer onto tared glass-fiber filters (Whatman grade 934 AH). The filters were dried at 85° C and weighed to ±0.1 mg. For each site and date, the ash and P content of the epilithon were estimated with three to five samples randomly chosen from those field samples whose dry weight exceeded 150 mg; this was necessary in order to have sufficient mass to conduct both analyses on the same sample. Epilithon ash content was determined by dry ashing at 450° C in tared crucibles and weighing to ± 0.1 mg. Epilithon P content was determined either by the ascorbic acid method (APHA 1992), or by inductively-coupled plasma atomic emission spectroscopy (Leeman Labs, Inc., Lowell, MA, model PlasmaSpec 2.5) , after wet digestion with concentrated sulfuric and nitric acids (APHA 1992).

2.2.2.4 Macrophytes and Epiphytes

Macrophytes were dried to constant weight at 105 °C, weighed, and then ground in a Wiley mill. Weighed subsamples were later digested in hot H_2SO_4 - HNO_3 for subsequent TP analysis using EPA Method 365.2. In the lab the bottles containing epiphytes and host macrophytes were shaken for 1.5 minutes (Jones 1980) to detach epiphytes from host plants. The macrophyte stems and leaves were removed from the bottle, dried and weighed. The suspended epiphytes were collected by filtering them onto preweighed 0.45 µm membrane filters which were subsequently dried and reweighed. The filters and epiphytes were then digested in hot acid and analyzed for TP employing the same methods as used for macrophytes.

2.2.2.5 Detritus

CPOM, wood and suspended detrital samples returned to the laboratory were oven dried at 105° C before being weighed. Approximately 40% of the collected CPOM samples, as well as several wood samples and all suspended detrital samples were ground in a Wiley mill, redried and weighed prior to phosphorus analysis. All samples were digested in a hot H_2SO_4 - HNO_3 solution (APHA, 1989) prior to analysis for P using the ascorbic acid method (EPA Method 365.2) and either an autoanalyzer or spectrophotometer.

2.2.3 Data Analyses

For each site, the raw data for all stocks were reduced to seasonal means with associated standard errors and were analyzed graphically. Additional data analyses specific to individual stocks are described below.

2.2.3.1 Water

Phosphorus concentrations in water are reported separately for the upstream and downstream ends of each reach as the arithmetic means of the 3-6 samples taken along each transect (Table 3.1). No significant differences between upstream and downstream P concentrations were observed for any sampling date. Consequently, for estimation of water stock, the water P concentration in the reach was represented as the mean of all samples for that date, both upstream and downstream. Water volume in the reach was estimated based on surveys of reach dimensions, observed water depths, and flow rate. Water P stock was calculated as the product of mean reach P concentration and estimated reach volume, then standardized to the area of the reach.

2.2.3.2 Sediments

The data analysis of the sediment compartment consisted of calculating P concentration means, standard deviations and standard errors for each site at each sampling time. To extrapolate the P concentration results to a reach scale (mg P/m^2 per depth interval) sediment densities for each sample were calculated (g/cm^3). The sediment volume for the Bacon Dr. samples was obtained by measuring the inside volume of the core barrels. The entire sediment interval dry weight was calculated by first weighing the entire sample interval to obtain a wet sample weight. A subsample was then weighed wet, oven dried and weighed again. The difference in weights was used to obtain the percent water. This number was used with the whole sample wet weight to calculate the total amount of dry sediment per interval sampled. The sample dry weight was divided by the volume to give a sediment density. The Spear St. site sediment densities were calculated slightly differently because samples were split into size fractions before analysis. Sediment volume was measured using a graduated cylinder. The gravel and sand fraction dry weights were obtained by oven drying. The silt+clay fraction dry weight was calculated by pipette method (Folk 1980). All sample fraction dry weights were combined and divided by the volume to obtain the sediment sample density. The sediment density was multiplied by the P concentration to yield mass of P per volume (mg P/cm^3). The statistical analysis used to compare within site interaction and between site interactions was a two-way ANOVA at a 95% confidence interval. The log of the means were plotted against the log of the standard deviation and the residuals were plotted against the predicted values to check assumptions of normality. All populations were considered normal and no data transformations were used.

2.2.3.3 Epilithon

Dry weights were normalized to a unit area (m^2) of rock surface by planar projection and scaled to a unit area (m^2) of each reach by adjusting for the percentage of the reach that supported epilithon. Ash-free dry mass (AFDM) and P stock per unit area of substrate were calculated with the % ash and % P means for each sample day. These estimates were also scaled to the reach in the same way that dry weights were. Propagation of error calculations allowed error estimates of the derived quantities. Graphical and regression analyses were used to test the relationship between dry weight and AFDM, and between P stock and AFDM. Two-way ANOVA was used to test the influence of site, season, and site-season interaction on dry weight. For this analysis, the 1994 sample dates were used since sampling during 1993 and 1995 did not extend to all seasons. A variance versus mean plot and analysis of residuals from the ANOVA indicated the need to log-transform the data to stabilize the variance (Morin and Cattaneo 1992). Pairwise comparisons of the two sites at each season were conducted with least significance difference (LSD) two-tailed t tests.

2.2.3.4 Macrophytes and Epiphytes

Data analysis for the macrophyte and epiphyte compartments consisted of calculating means and standard errors for biomass, P content, and P storage for each site at each sampling time. Analysis of variance was not done due to the mixture of sampling schemes employed (random quadrat sampling when biomass was low versus stratified random sampling when it was high). When stratified random sampling was employed, strata means for macrophyte biomass were estimated and weighted by strata stream coverage prior to determination of the mean for the stream as a whole. The P stock associated with macrophytes in the stream reaches was estimated as the product of mean macrophyte biomass in the reach and mean macrophyte P content. Propagation of error calculations allowed error estimates of the derived quantities.

The dry weights of epiphyte samples collected from macrophytes were normalized to the dry weights of the host macrophytes to yield estimates of "specific mass" (g epiphyte/g macrophyte). Epiphyte biomass in the stream reaches then was estimated as the product of the mean epiphyte specific mass and mean macrophyte biomass in the reach. Because epiphytes were collected only at the Bacon Dr. site, estimates of epiphyte biomass and P stock at Spear were made using the values for specific epiphyte mass and epiphyte P obtained at the former site. In addition, epiphyte sampling was confined to summer and fall, when plant biomass was appreciable. To estimate the epiphyte biomass and P stock associated with the meager plant stock present in winter and spring, the study means for epiphyte specific mass and P content were used.

2.2.3.5 Detritus

Three types of detritus were analyzed during this study: CPOM on the bottom, CPOM in suspension, and wood. For each site at each time, means and standard errors for bottom CPOM mass , P content and P storage were made. Subsequently, two-way ANOVAs on log-transformed data were performed to test for site, season and site X season effects on CPOM. Finally, pairwise comparisons of the two sites at each season were conducted with LSD two-tailed t tests.

To calculate wood mass in the stream reaches from the data obtained on wood dimensions (length and radius of each stick or log present), we first assumed that each wood piece was a cylinder and calculated its individual volume. Next, we summed the volumes of all pieces collected in a transect and divided this value by transect area (length X width) to arrive at an estimate of wood volume per unit area. Wood samples were collected throughout the course of the study to estimate wood density (each was measured, dried and weighed; density= mass/volume). Areal wood volume times wood density yielded estimates of areal wood mass. The wood samples brought into the laboratory were also analyzed for P. We estimated the P stock in wood as the product of P content and areal wood mass. Two-way ANOVAs were used to examine the influence of site and season on wood mass in the stream.

Estimates of suspended detritus (CPOM) in stream reaches were based on the catch of detritus traps which were faced into the stream flow for two hours (Section 2.2.1.5). The following equation was used to estimate the standing stock of suspended detritus (S,):

$$S = (M_c/(A_c \cdot V \cdot T_c)) \cdot D_{(ave)}$$

S = instantaneous standing stock (g/m^2)
M_c = mass collected (g dry weight)
A_c = area of trapping surface (m^2)
V = water velocity (m/min)
T_c = length of collection period (min)
$D_{(ave)}$ = mean stream depth in the reach (m; to allow for conversion of volumetric mass to g/m^2

Suspended detritus was not trapped during the winter due to the difficulties of working under a continuous ice cover.

The P stock in suspended CPOM was estimated from the areal estimates of mass and the average P contents of the catch. Because we obtained just one suspended CPOM sample per trapping, we pooled site data to estimate mean P contents. The rate of P flux downstream in suspended CPOM was estimated from the suspended CPOM standing stock and water discharge. No analysis of variance could be done on the suspended CPOM data due to lack of sample replication.

2.3 BIOAVAILABLE PHOSPHORUS

Bioavailable P (BAP) was estimated on three occasions (Summer 1994, Fall 1994 and Spring 1995) with the Selenastrum capricornutum Printz bioassay by measuring increase in cell density according to standard procedures (Miller et al. 1978). Samples were autoclaved prior to bioassay. Cell density increased linearly in the graded series of external phosphate standards (typical $R^2 = 0.98$); however, recovery of the internal standards indicated inhibition on some occasions and stimulation on others which necessitated corrections of ± 10 to 40%. In June 1995, BAP was estimated with $^{33}P\text{-}PO_4$ by using the Rigler assay (Rigler 1966).

2.4 RADIOTRACER EXPERIMENTS TO MEASURE P UPTAKE

2.4.1 General Approach

To estimate the flux of P between different stream compartments within the LaPlatte River, it was necessary to bring water, epilithon-colonized rocks, detritus, plants and sediments into the laboratory and conduct radiotracer assays. The basic approach was to add a radioisotope of P, either ^{32}P or ^{33}P, to one P compartment and monitor its appearance in other compartments. Because our principal interest was biological uptake, the label was always added to stream water or to sediment pore water, and its uptake by living organisms monitored. In some cases, loss of radioisotope from the donor compartment rather than accumulation in receiving compartments was followed. The ^{32}P or ^{33}P-labelled molecules functioned as "tags" on the phosphate molecules in the compartment to which they were added. From the data on the rate of radiotracer transfer between compartments, a rate constant for P transfer (k (1/min), which is relevant for both ^{31}P (normal P) and $^{32/33}P$) could be calculated. This rate constant was multiplied by the concentration of ^{31}P in the donating compartment to arrive at estimates of ^{31}P flux. Because we always added ^{32}P or ^{33}P as orthophosphate, the fluxes that we estimated involved the movement of this particular P form.

The radiotracer method assumes that: 1) organisms taking up orthophosphate do not discriminate between ^{31}P, ^{32}P and ^{33}P (there is considerable literature showing that discrimination is minimal); 2) that the radioisotope is added in trace amounts relative to the unlabelled P present (so that it does not influence P dynamics; we met this requirement by using carrier-free ^{32}P or ^{33}P); and 3) that the compartments involved in the radiotracer transfer are well mixed (we assumed this requirement was met). All radiotracer work was done in "microcosm" systems in the laboratory to avoid contamination of the stream environment.

The calculation of a rate constant for P transfer is relatively straightforward when an experimental system is restricted to two compartments. This was the case for our studies of phosphate uptake by epilithon and by the biofilm on detritus. The general equation for the two model system is:

$$y_t = y_{asymp.t} + (y_0 - y_{asymp.0})e^{-kt},$$

where y_t is the radioactivity in the water at time t,

y_0 is the radioactivity in the water at the initiation of the experiment,

$y_{asymp.0}$ and $y_{asymp.t}$

are the asymptotic values for radioactivity in the water at times zero and t,

k is the rate constant for P transfer, and t is time,

$$\text{or:} \quad \ln y_t = \ln y_{asymp.t} + \ln (y_o - y_{asymp.0}) - kt.$$

Because, in our systems, the amount of P in particulate form (in organisms) greatly exceeded the amount of PO_4-P in the water, the asymptotic value for P in the water ($Y_{asymp.0 \text{ or } t}$) was assumed to be zero, thus further simplifying the equation to:

$$\ln y_t = \ln y_o - kt$$

$$\text{or:} \quad k = \ln(y_t/y_0)/t.$$

Rate constants, therefore, could be obtained through linear regressions of either ln % (^{33}P or ^{32}P in solution) on time, or ln (^{33}P or ^{32}P activity in solution) on time (the two regressions give the same rate constants). Normally, the above functions were plotted prior to completing regressions to look for nonlinearities. Biphasic and multiphasic curves suggested radiotracer return from the receiving compartment (via leakage or sloughing), or, alternatively, multiple mechanisms for uptake. When nonlinearities were observed, only those data points fitting the initial linear portions of the uptake curves were used in the calculation of rate constants. This practice reduced errors related to feedback, but meant that only the faster-paced P fluxes were estimated.

The rate constants for macrophyte and epiphyte uptake could not be calculated using the above procedure because the microcosm systems used to study these organisms included four compartments (plants, epiphytes, water, and sediment), all of which influenced the ^{32}P dynamics of the others. It was necessary then to estimate rate constants through curve fitting to numerical solutions of the differential equations describing P transfer between the four compartments. The software for this task was written by M. Braner (pers. comm. 1995), and is available on request.

Rate constants were multiplied by estimates of orthophosphate-P concentrations to arrive at estimates of gross P flux from water to the various compartments. Like many other investigators (Wetzel 1983), we found evidence that in our study stream SRP concentration was substantially greater than PO_4-P concentration (see Section 3.2.2). Because a reliable analytical technique for analyzing orthophosphate in the presence of interfering colloidal compounds does not exist, we chose to use as our estimate of PO_4-P the values obtained for BAP. Because the alga used in the BAP assays can use simple organic forms of P as well as phosphate, our estimates of PO_4-P concentration may be overestimates, and our flux estimates may consequently be too high.

Individual experiments are described in detail below.

2.4.2 Epilithon

Short-term uptake of phosphate by epilithic periphyton was determined during the summer and fall of 1994 and in late spring 1995 using $^{33}P\text{-}PO_4$ and the method of Steinman et al. (1991). Eight to sixteen rocks were selected from the study reach (average surface area: 37.1 (± 4.3, 1 SE) cm^2) and placed into eight 2 L polycarbonate containers with 1.0 L of 0.45 µm filtered river water. Adsorption controls (no rocks) and killed controls (autoclaved rocks) were also included. Each container was stirred with a magnetic stir bar set to 500 rpm with a strobe; this created a flow rate over the rocks of about 12 cm/s. Approximately 185 kBq of carrier-free $^{33}PO_4$ was added to each container. Light intensity was set at 300 $\mu E/m^2/s$ (PAR) and average temperature was within 2 to 3°C of ambient river water. One ml samples were collected at timed intervals, filtered and added to CytoScintTM liquid scintillation solution (ICN Radiochemicals, Irvine, CA) for counting. Samples were collected at approximately 8-minute intervals for up to one hour and then at 20- to 30-minute intervals for up to five hours. The difference between initial and final samples showed that between 60 and 70% of the phosphate was removed over this time interval. The first-order rate constants of phosphate depletion were calculated from the initial exponential portion of the depletion curves after logarithmic transformation (as described above). Total phosphate uptake was calculated from these rate constants by multiplying them by the bioavailable P concentration determined by bioassay, and results were expressed per unit area of rock surface and per gram dry weight of periphyton. During Spring 1995, flux determination (when BAP data were not available), phosphate additions of 0, 4, 10, 20 and 40 µg P/L above ambient were added to facilitate estimation of available phosphate by the Rigler assay method (Rigler 1966).

2.4.3 Macrophytes and Epiphytes

Phosphorus uptake by LaPlatte River macrophytes and epiphytes was studied in plexiglass microcosms (79 x 40 x 40 cm) with a recirculating throughflow of river water (Figure 2.5).

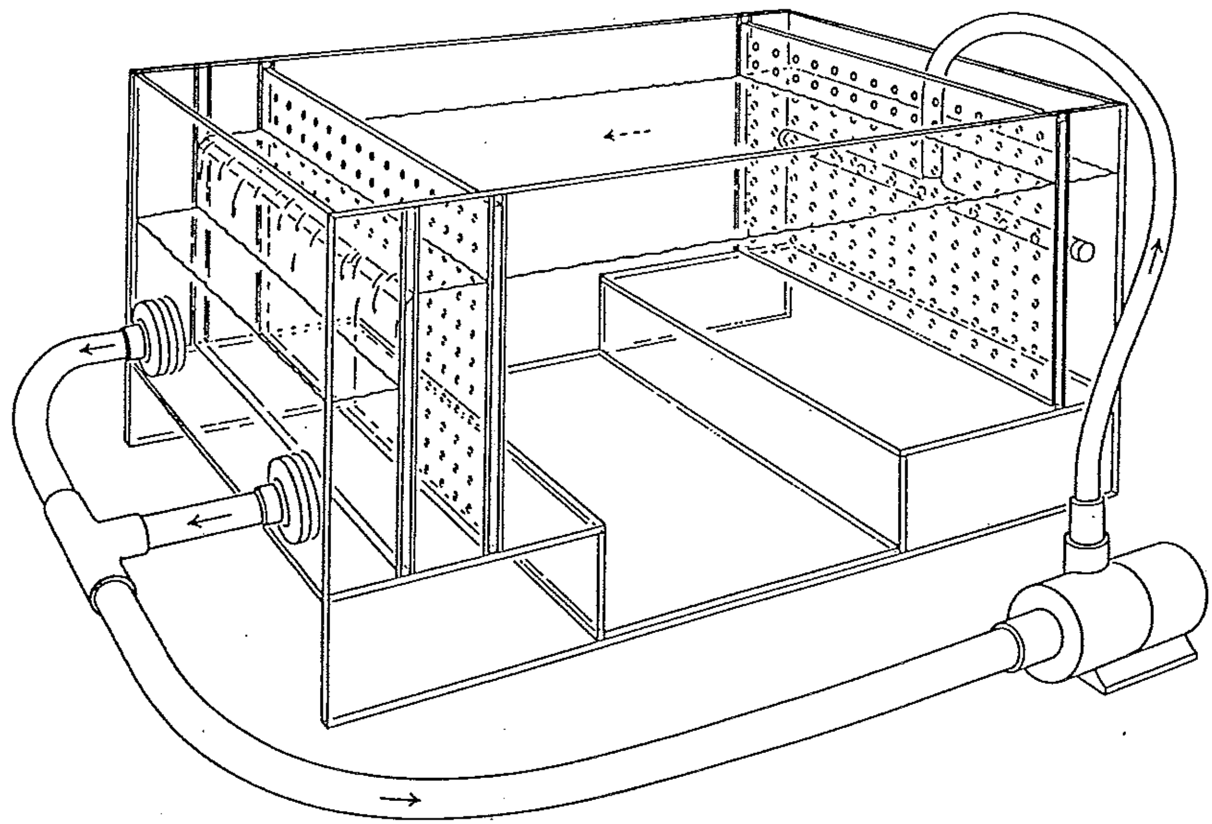


Figure 2.5 Stream microcosm designed to study P uptake by LaPlatte River macrophytes and epiphytes. Plant and soil plugs sat in the recessed chamber at center.

Each microcosm contained a removable tray which was filled in the field with cores of sediments and plants. All three of the plants common to the LaPlatte River (*Elodea canadensis*, *Potomogeton pectinatus*, and *P. natans*) were included in each tray. A recessed chamber in the microcosm held the tray of sediments so that the sediment surface lay flush with the floor of the larger chamber, and water flowed through plant stems and over sediments. Plants and sediments were collected exclusively from the Bacon Dr site, as collections from Spear St. would have depleted the scant stock present there. The microcosms were maintained on a wet table in the laboratory under a bank of VHO fluorescent lights (~300 $\mu E/m^2/s$; with light-dark cycles). Water flow rates (~40 cm/min, created by centrifugal pumps) were in the range observed at the Bacon Dr. site during summer low flow.

Three separate flux experiments (summarized in Table 2.2) were run during August and September 1994. In each experiment, there were two treatments, each with three replicate stream microcosms for a total of 6 microcosms. Experiment 1 examined phosphate uptake from the water by macrophytes and epiphytes at both ambient and elevated P concentrations. Thus, ^{32}P was added to the water of the 6 microcosms. The second experiment measured phosphate uptake by macrophytes from sediment under ambient versus elevated water P concentrations. Thus, in this experiment, radiotracer was added to the sediment of the 6 microcosms, using a syringe and needle and following a grid pattern. Experiment 3 compared phosphate uptake by macrophytes from water and sediments at ambient water phosphorus concentrations. ^{32}P was added to the water of half the microcosms ('Labelled Water') and to the sediment of the other half ('Labelled Sediment').

In all three experiments, ^{32}P loss from water and accumulation into macrophytes and epiphytes was monitored for 3 days (water was sampled at 0.25, 0.50, 1, 2, 5, 10, 24 hr

Table 2.2 Summary of artificial stream experimental design.

Experiment	Microcosms 1-3	Microcosms 4-6
Experiment 1	Ambient Water SRP	SRP Enriched 8X
8/12/94	'Ambient P'	'Enriched P'
	^{32}P Added to Water	
Experiment 2	Ambient Water SRP	SRP Enriched 5X
8/25/94	'Ambient P'	'Enriched P'
	^{32}P Added to Sediment	
Experiment 3	^{32}P Added to Water	^{32}P Added to Sediment
9/14/94	'Labelled Water'	'Labelled Sediment'
	Ambient Water SRP	

on the first day, and once a day, thereafter; plant and epiphyte material were collected daily). Water samples (15 ml; 3 per microcosm per sampling) were collected directly into scintillation vials using a 5 ml automatic pipet. Plant samples (one or two from each species of plant present) were obtained by cutting 4-6 cm of stem and leaf from the top of plants in the chambers, placing the fragments in a bottle for shaking to remove epiphytes, and then transferring the plants to tins. The epiphytes released into the bottle were concentrated by filtering them onto 0.45 μm preweighed filters.

On the third day, the artificial streams were broken down. Water was drained from the microcosms, with care taken to avoid disturbing the sediment-water interface, and samples of sediment and tank wall algae were collected. Wall algae were sampled by wiping 10 cm x 10 cm patches with membrane filters. One sample was taken from a side wall and one from the inside surface of each baffle (the sides facing the experimental area). The filters were then digested and analyzed for ^{32}P activity. Two types of sediment were present in the microcosms; sediment cored along with the pondweed species had a higher clay and lower sand content than the sediments in cores of *Elodea*. Sediment samples (6 per tank; 3 from each of the two sediment types) were collected by coring with a 10 cc cutoff syringe. The triplicate samples from each sediment type were aggregated and then centrifuged (30 min, 3500 rpm) to separate pore water from bulk sediments. Pore water was passed through a 0.45 μm filter into a scintillation vial prior to counting for ^{32}P. The remaining sediments were dried, weighed, subsampled and combusted at 450° C for 3 hours to ensure high recovery of P from organic material upon digestion. After combustion, sediments were digested in a hot, concentrated H_2SO_4 and HNO_3 solution (Section 2.2.2.4) in preparation for ^{32}P analysis.

Samples were analyzed for ^{32}P using the Cerenkov counting method (counting in water). Because the media of the different sample types varied, counting efficiency (counts per minute (cpm)/disintegrations per minute (dpm)) was determined separately for each sample type by adding known amounts of tracer (known dpm) to sample material and measuring the cpm. Research results are reported in dpm. These results also are corrected for ^{32}P decay; the counts reported below are for dpm ^{32}P at the time of radiotracer delivery to the microcosms.

Rate constants were determined for P exchange between water or sediment and plants and epiphytes using the numerical model described above. Measurement of unlabelled P concentrations in tank plants, epiphytes, sediments, and water also were made to facilitate the calculation of P fluxes from rate constants and P concentrations.

2.4.4 Detritus

Phosphate may be removed from solution by detritus both through surface adsorption and active P assimilation by decomposers. Nutrient uptake by detrital bacteria and fungi is referred to as "leaf conditioning", and was found to be a major P flux within Walker Branch, TN (Mulholland et al. 1985). To estimate phosphate flux from water to detritus in the LaPlatte, three types of stream detritus, tree leaves (box elder), macrophyte debris (leaves from floating leaf pondweed), and small pieces of wood, were collected from the stream and brought into the laboratory. Each specimen (3 of each detritus type) was placed in a beaker containing 150 ml of stream water, and fed a tracer amount (~10 μCi) of $^{32}PO_4$.

The time course of radiotracer disappearance from the water then was followed for 24 hours (ambient stream temperatures were maintained by keeping the beakers in a constant temperature water bath). Ten milliliter aliquots of water were removed and filtered through

GFF filters (to remove any detrital fragments) at about 1, 5 , 10, 30, and 60 minutes, and 5, 10, and 24 hours after isotope addition. The amount of ^{32}P present in the filtrate of samples (i.e., remaining in the water) was determined using Cerenkov counting in a liquid scintillation counter (see Section 2.4.3). The rate constant for uptake was determined from the slope of the relationship in $\%^{32}P$ in filtrate versus time (see Section 2.4.1), and fluxes by multiplying rate constants by BAP concentration. Beakers receiving ^{32}P but not containing detritus were included in the experiment to correct for radiotracer adsorption onto beaker walls.

2.5 ASSESSMENT OF NUTRIENT LIMITATION OF EPILITHON

During Spring 1995, nutrient-diffusing substrates (Fairchild et al. 1985) were placed at the Spear St. site to test if epilithon growth responded to elevated nitrogen or phosphorus levels. Clay saucers (11.0 cm dia.) were filled with either 2.0% agar alone (C), agar plus 0.05 M Na_2HPO_4 (P), agar plus 0.5 M $NaNO_3$ (N), or agar plus both nutrient concentrations combined (N+P). The open end of each saucer was sealed with a 9 cm plastic petri dish cover and silicone caulk. Each treatment was replicated four times and attached to rectangular concrete paving stones in a randomized complete block design. The paving stones were placed in the river normal to the flow for 28 d and then brought back to the laboratory for analysis. Water samples were collected on Day 28 for determination of both phosphorus and nitrogen concentrations.

2.6 SEDIMENT-P ADSORPTION AND DESORPTION

Sediment samples from the Bacon Dr. reach were collected by hand-inserting plastic core barrels into the bottom sediments and capping them *in situ.* River water was collected in prewashed, acclimated, plastic or glass jugs. Collected materials were immediately returned to the lab, where the river water was filtered through Gelman AE glass fiber filters (nominal pore size = 1 μm). This filtered river water (FRW) was then used as the solution matrix for the adsorption studies. In addition, distilled water (DW) was also used as a solution matrix in the investigation of adsorption rate. In all instances, KH_2PO_4 was used as the P source for additions and analyses for soluble reactive phosphorus (SRP) were done using EPA Method 365.2.

In order to determine the adsorption isotherm, known weights of wet sediment (equivalent to approximately 2 gm of dry sediment) were placed in centrifuge tubes, and 30 ml of solution were added to each. The solution consisted of FRW plus spikes of P producing known initial phosphorus concentrations. One sample was mixed with unspiked FRW and one sample was mixed with unspiked DW. These sediment slurries were shaken for 24 hours, centrifuged at 10,000 rpm for 12 minutes, and the supernatant decanted for analysis. The tubes, wet sediment and residual supernatant were reweighed and 30 ml of unspiked FRW were added to each. This slurry was shaken for 8 hours, re-centrifuged and the supernatant was decanted for analysis to determine P release. Sediment dry weight equivalents were determined by weighing three sediment aliquots before and after drying for 24 hours at 60° C, with the average ratio of dry weight/wet weight being used to convert all analyses to a dry weight sediment basis. The pH of samples was measured before and after agitation (pH before ranged from 7.4 to 7.7, except for the DW water which was 4.50; pH after agitation ranged from 6.8 to 7.3, so no pH adjustment was made prior to analysis).

In order to ascertain rate of adsorption, wet sediment (equivalent to approximately 2 gm of dry sediment) was placed in centrifuge tubes and 30 ml of FRW or DW, spiked to yield a standard addition of 1000 μg P/liter, was added. Samples were agitated for time intervals of 0.05, 0.33, 0.66, 1.25, 3, 6, 12, or 24 hours, after which they were filtered through

0.45 μm membrane filters or centrifuged at 10,000 rpm for 12 minutes. The supernatant was then analyzed for SRP. To those samples that had been shaken for 24 hours, 30 ml of either FRW or DW without a P spike were added, samples shaken for 24 hours, again centrifuged and the supernatant analyzed to determine the amount of P released.

2.7 STUDIES OF DETRITAL P TRANSPORT AND P RELEASE FROM DETRITUS VIA DECOMPOSITION

2.7.1 Detrital P Transport

To examine the amount of detritus transported past the stream reaches each day and the size range of the detritus transported, we constructed the detritus traps described in Section 2.2.1.5. These traps, which collected suspended detritus in three size categories, >1.68 cm^2, 0.3-1.68 cm^2, 0.01-0.30 cm^2, were deployed not only during stock assessment periods (except in winter, when ice cover prevented their placement on the bottom) but also on several occasions during the summer and fall of 1994. Our objective in conducting many analyses was to relate suspended detrital flux (the detrital mass collected per m^2 cross section per unit time) and particle size distribution to stream discharge, as well as to season and stream reach. Thus, each trapping event was accompanied by measurements of water velocity and depth.

2.7.2 Detrital P Release

To estimate the rate of P release from decaying allochthonous leaves and macrophyte debris in the stream reaches, litter bag experiments were performed during the fall of 1994. The litter bags were 6 X 5 cm in size, were made of 5 mm nylon mesh, and were filled with approximately two grams of leaf or macrophyte material (precisely weighed). Leaves from three of the most common streamside tree species, *Acer negundo* (box elder), *Tilia american* a (basswood) and *Ulmus americana* (american elm) (all collected in autumn immediately after abscission), and stems and leaves from the three dominant macrophytes

Elodea canadensis (waterweed), *Potamogeton natans* (common floating pondweed) and *Potamogeton pectinatus* (sago pondweed), were included in the study. Macrophytes were collected at the end of the growth season, while the plants were still alive, but in a senescent state. *Elodea*, which can overwinter, was killed through tyndalization (mild steaming). Filled bags were tied to concrete blocks in the stream, and then collected over a time series (0, 3, 7, 14, 28 and 56 days). Because sediment accumulated in the bags, leaves were rinsed with distilled water prior to weighing. Wet weights were converted to dry weights using a conversion factor obtained by comparing the weights of freshly collected plant material before and after drying. The weight of the sediments trapped in the litter bags was also assessed, and subsamples of litter material and sediments were digested and analyzed for TP (section 2.2.2.5).

2.8 P ATTENUATION EXPERIMENTS

Two experiments were conducted to monitor the transport of a pulse of dissolved P through the main stem of the LaPlatte River. Phosphorus was added to the river and measured on a 3 km reach from Carpenter Road to Spear St. (see Figure 2.1). The original proposal called for three such experiments to be conducted under different physical/biological conditions: winter low flow, summer low flow, and summer high flow. Because of the extreme drought in Summer 1995, only the first two experiments could be carried out.

To account for dilution and to indicate the first arrival of the pulse, a conservative tracer was used in addition to the P. Initial plans to use NaCl as a tracer were abandoned after several pre-tests revealed that the quantity of salt required would have likely altered biological response in the river. Instead, Rhodamine WT dye (FWT Red Liquid 50, Formulabs, Piqua, OH), detectable to 1 ppb using a fluorometer, was used as a tracer. Several small-scale pre-tests were conducted to calibrate dye addition and detection techniques and to assess likely times of travel through the study reach. Because of the extremely long travel times measured, original plans to conduct the experiment over a long section of the LaPlatte River from Carpenter Road to Bacon Drive were abandoned in favor of the shorter reach from Carpenter Road to Spear Street.

The winter low-flow experiment took place on December 20, 1994. The P addition consisted of 0.89 kg P in the form of 0-50-0 P_2O_5 fertilizer; 1 liter of Rhodamine WT (5%) was also added (57.5 g active ingredient). The summer low flow experiment was conducted from June 11-13, 1995, with the addition of 1.14 kg P as KH_2PO_4, and 1 liter of dye. For both experiments, the P and the dye were mixed together in approximately 50 - 80 liters of river water and dumped simultaneously into the stream at a point of concentrated flow in the stream cross-section.

At the downstream site (Spear St.), grab samples were collected every ten minutes in a similar manner to the stock assessment water sampling described above. Each of these samples was immediately tested for fluorescence on-site in a Turner-Sequoia Model 111 Fluorometer. If no fluorescence was detected, most samples were discarded, but hourly samples were retained for measurement of pre-pulse background P concentration. When fluorescence was detected, all subsequent samples were retained for P analysis. Because fluorometer performance was slightly impaired by field conditions, the three samples immediately preceding the first field dye detection were also retained for later analysis under more controlled laboratory conditions. Regular grab sampling was maintained even after dye was no longer detected for as long as resources permitted, approximately another ten hours in the first experiment and another 20 hours in the second.

All samples were stored on ice and transported to the UVM water resources lab at the end of the experiment. Samples were immediately re-analyzed in the fluorometer, and a series of Rhodamine standards was run so that actual Rhodamine concentrations could be calculated. Remaining sample water was then acidified and stored for P analysis as described above. All samples from both attenuation experiments were analyzed for TP only. Samples from the December, 1994 experiment were analyzed for TP in the UVM laboratory as described above; samples from the June, 1995 experiment were sent to the Department of Environmental Conservation laboratory where P analysis was conducted by methods described in Section 2.2.2.

2.9 MODEL DEVELOPMENT

One of the specific objectives of this project was to develop an initial dynamic simulation model to describe P-cycling, transport,and storage based on understanding of the underlying processes occurring in the stream. The "Dynamic Stream Phosphorus Model" (DSPM) is based upon several fundamental notions regarding the nature of P transport, transformation and storage within a stream reach:

a) at any instant in time all the phosphorus in the stream reach is located within five compartments (either in the water, epilithon, macrophytes, sediments, or detritus contained within the boundaries of the reach). Thus, the quantities of P in various storage compartments in two reaches of the LaPlatte River were measured during this project period and the DSPM structure incorporates these five compartments.

(b) physical, chemical, and biological processes operate within the reach to transform P within the compartments, to move the P between compartments and to transport the P through the reach (these processes result in P fluxes, that is the streaming of P from one compartment to another). The DSPM quantified such fluxes with appropriate quantitative algorithms based upon field and laboratory measurements made during the project.

(c) the relative ability of an individual compartment to store P as well as the transport/transformation mechanisms and ratios within and between compartments are controlled by: 1) physical characteristics of the reach; 2) flow within a reach; 3) concentration of P in the streamflow entering a reach.

Figure 1.2 is a schematic description of the conceptual model upon which this project has been based. The stream reach is shown as having length and depth and being comprised of the five compartments (Water TP, Macrophyte TP, Periphyton (epilithon) TP, Detritus TP and Sediment TP) in which all TP (TP is the phosphorus measured by the Total Phosphorus analysis and is the sum of the soluble and particulate fractions as differentiated by filtration through a 0.45 μm standard filter. SP is the soluble fraction, and PP the particulate fraction of TP) in the reach is stored. Figure 1.2 also shows that there are TP inputs entering the stream reach and TP outputs leaving the stream reach. Thus, the stream reach is an open system as is typical of all natural ecosystems. The arrows in Figure 1.2 represent the transformation and transport processes or fluxes that function within the reach. Solid arrows represent the soluble fraction (soluble phosphorus or SP) of the total phosphorus (TP) and the dashed arrows are the particulate fraction (particulate phosphorus or PP) of the TP. The horizontal arrows represent the transport of both SP and PP through the reach with the moving water, the process of advection. If the water flow is fast, this movement is rapid, while if the flow is sluggish, the movement is slow. The vertical arrows represent the various physical, chemical and biological mechanisms that function to move phosphorus from one compartment to another. The arrows are shown to be unidirectional to allow identification and description of the individual processes that are functioning in the reach.

Most of the vertical arrows (and all of the horizontal arrows) represent processes that move phosphorus either into or out of the Water TP compartment. All such processes can influence the amount of TP in the Water TP compartment and consequently the concentration of TP in the outflow from the stream reach. Under certain circumstances one of the vertical arrows (a particular transformation process) may dominate TP movement into or out of the Water TP compartment, while under other conditions another process may become the dominant process. In reality, the transformation and transport processes identified in Figure 1.2 are operating simultaneously and interactively thus providing the basis for feedback behavior so typical of these ecosystems. Thus, the dynamics of how the stream reach processes TP is difficult to describe, let alone understand, even with this simplified model. An even more simplified description of the stream reach ecosystem appears to be warranted, but with additional simplification even greater care must be exercised to assure model competency.

Figure 2.6 shows the conceptual project model, a block and arrow diagram, that is the simplified description of the stream reach ecosystem and illustrates the exact configuration of the DSPM. This figure incorporates the TP Input, TP Output and TP transformation processes in a manner so that they may function simultaneously and provide feedback behavior. The rectangular objects represent six TP storage compartments (Water SP, Water PP, Macrophyte TP, Periphyton TP, Detritus TP and Sediment TP). The arrows represent the TP fluxes into and out of the compartments and into and out of the reach itself. The bold arrows are the TP Input and TP Output fluxes to and from the stream reach, respectively. The less-bold, narrow arrows represent the inter-compartmental transformation/cycling P fluxes. It is possible for TP to be moving simultaneously into and out of any and/or all compartments and into and out of the reach.

The structure shown in Figure 2.6 is the basis for formulating the initial dynamic simulation model (DSPM) within the object-oriented programming environment provided by STELLA II (Peterson and Richmond 1993). Within the STELLA platform, constructs

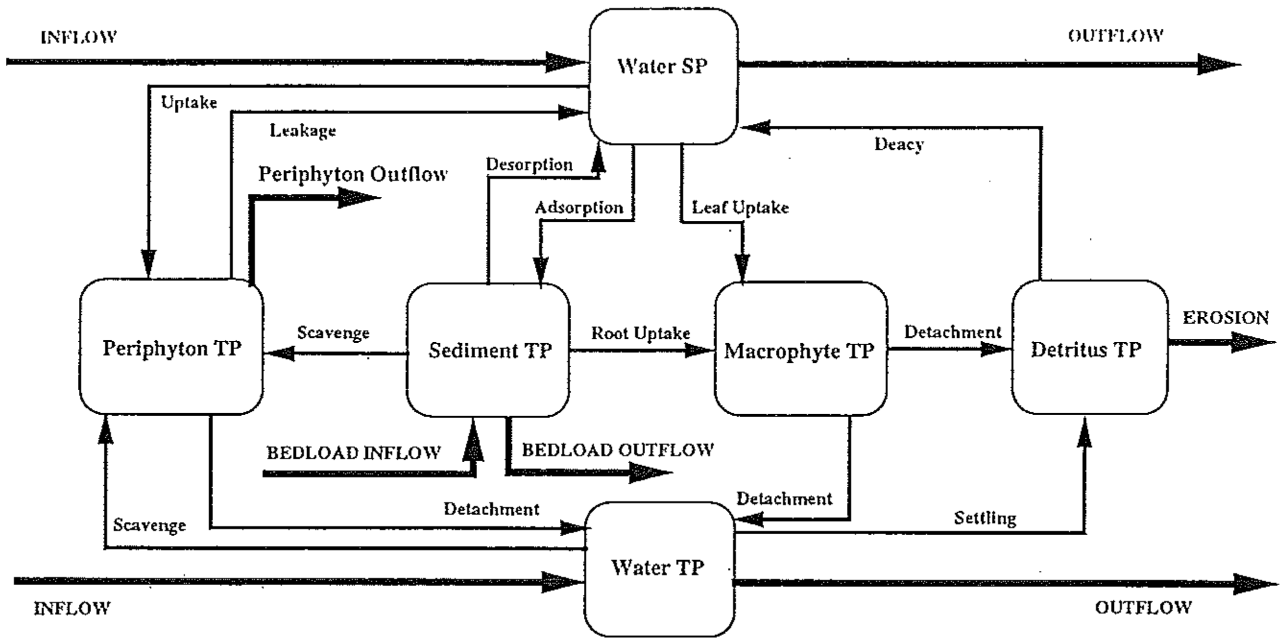


Figure 2.6 Schematic description of the project conceptual model. The diagram divides the reach into five compartments (water TP, macrophyte TP, periphyton TP, detritus TP, and sediment TP) for storing TP in the reach and shows the various physical, chemical, and biological mechanisms that function to move phosphorus from one compartment to another (vertical arrows) as well as water movement that transports TP through the reach (horizontal arrows). Solid and dashed arrows represent the soluble and particulate fractions of the TP, respectively. The diagram also shows the TP inputs and outputs to and from the stream reach.

include "stocks" which represent storage components, "flows" which represent rates at which material is added to or removed from stocks and "converters" which are used to provide mechanisms for controlling, manipulating and modifying stocks and flows. The actual STELLA II Structural diagram for the DSPM is given in Appendix A. The various objects shown on the STELLA II structural diagram are all identified by their DSPM Variable Name. The layout of the portion of the structural diagram that is within the "Integration Module for Phosphorus Transformation and Transport in a Stream Reach" emulates the structure shown in Figure 2.6.

All dynamic models require the input of certain data so that a simulation experiment can be run; in this regard the DSPM is typical. To promote understanding of how the DSPM describes P cycling, transport and storage in stream reaches it is useful to classify the required input data needs into functional categories. All data inputs for the DSPM are summarized and divided into the nine separate categories shown in Table 2.3 .

The first category (Inputs to Stream Reach) includes those inputs that define the input stream flow and chemical characteristics of the stream flow that enter the stream reach of interest. Included here is the input streamflow, the inflow concentration of total phosphorus (TP), the inflow concentration of the soluble phosphorus (SP) as well as the fraction of the SP that is bioavailable (BAP). By changing the values of these inputs, the DSPM can simulate conditions of low stream flow or high stream flow and, at the same time, the input values of TP, SP and BAP fraction can be changed to simulate an inflow either high or low in phosphorus concentration. The input stream flow and P concentration values can be varied over the time of the simulation so that the DSPM can emulate hydrographs and/or P chemographs for water entering the reach.

Table 2.3 Summary of input data requirements for the DSP Model (nine separate categories of input variables are listed)

INPUT PARAMETERS	DSPM Variable Name	Source of Input
1. Inputs to Stream Reach		Determined by user depending on input conditions that are desired during the simulation
Streamflow	Q in cfs	
Soluble P in Inflow	SP In mgl	
Total P in Inflow	TP In mgl	
Bio-Avail P Fraction	BAP Fraction	
2. Inputs Defining Stream Channel		Determined by field measurements of stream channel geometry and stream bottom deposits. Relationships calculated with Manning equatton.
Length of Stream Reach	Length of Reach m	Set = 1000 meters
Depth of Flow vs Streamflow	Depth Flow vs Q	
Average Velocity vs Streamflow	Avg Vel vs Q	
Hydraulic Radius vs Streamflow	Hyd Rad vs Q	
Slope of Stream Channel	Chan Slope	
Low Flow Stream Width	Width @LowQ m	
Median Dia of Fine Bottom Sediments	Sed Part Dia mm	
Bulk Density of Sediment	Sed Bulk Den	
Fract Bottom Area in Sediment	Sed Area Fract	
Fract Bottom Area in Epilithon Habitat	Epil Hab Area Fract	
Fract Bottom Area in Macrophyte Habitat	Mphy Hab Area Fract	
Initial Sediment Depth	Sed Init Depth	
Fractional Weight of silt/clay fraction	Wt Fract silt	
3. Inputs Defining Initial Conditions		Determined by user depending upon season of year during which simulation is run. See text.
Initial TP Conc in Algal Biomass	TP Algal Init mgPpgB	
Initial Areal Density of Algal Biomass	Algal Mass Init gBpa	
Initial Areal Density of Macrophyte TP Mass	Mphy Mass Init kgBpa	
Initial Areal Density of Detrital TP Mass	Detri Mass Init kgDpa	
Initial TP Conc in Sediment	TP Sed Init gPkgS	

Table 2.3 cont.

INPUT PARAMETERS	DSPM Variable Name	Source of Input
<u>4. Inputs Defining Time of Year of Simulation</u>		<u>Run Start Day selected by user. Adjustment factors derived from literature and field observation.</u>
Day of the Year on which Simulation Begins	Day of Run Start	
Seasonal Adjust of Algal Growth	Algal Gro Adj	
Seasonal Adjust of Macrophyte Growth	Mphy Gro Adj	
Seasonal Adjust of Macrophyte Sloughing	Mphy Slough Adj	
Seasonal Adjust of Detrital Decay	Detri Decay Adj	
Seasonal Adjust of Adsorption /Desorption	Adsorb Adj	
<u>5. Inputs Defining P Adsorption/Desorption</u>		<u>Derived from the literature, field observations and laboratory experiments, as appropriate.</u>
Max P Adsorptive Capacity of Sediment	Ads Max Cap Sed	
P Adsorption Affinity Constant of Sediment	Ads Affin K	
Thickness of Diffusion Boundary Layer	Diff BL Thick cm	
Fick's Law Diffusion Constant	Diff Const	
<u>6. Inputs Defining P Processing By Periphyton</u>		<u>Derived from the literature, field observations and laboratory experiments, as appropriate.</u>
Max Algal Growth Rate Constant	Algal mu max	
Max Algal P Uptake Rate Constant	P rho Max	
Half Saturation Constant for P Mass	Km P	
Half Saturation Constant of P Uptake	Ks 05u	
Max TP Concentration in Algal Biomass	TP Algal Max mgPgB	
Min TP Concentration in Algal Biomass	TP Algal Min mgPgB	
Max Areal Algal Biomass Density	Algal Mass Max gBpa	
Min Areal Algal Biomass Density	Algal Mass Min gBpa	
Percentage Ash in Periphytion Biomass	PerCent Ash Pphy	
P Leakage Rate Constant	Leak Rate Const	
Periphyton Slough Rate Constant	Pphy Slough Const	
Periphytion Erosion vs Velocity	Pphy Erosion Coeff	
Fraction Periphyton Detached to Bedload	Pphy Detach Fract	

Table 2.3 cont.

INPUT PARAMETERS	DSPM Variable Name	Source of Input
7. Inputs Defining P Transport by Sediment		Derived from the literature, field observations and laboratory experiments, as appropriate.
Kinematic Viscosity of Water	Kin Visc Water	
Specific Gravity of Sediment	Spec Grav Sed	
Specific Gravity of Water	Spec Grav Water	
Reference Conc of Bedload Transport	Bedload Ref Conc	
von Karmen's Constant	vonKarmen Const	
Gravity Constant	Grav Const	
8. Inputs Defining P Processing by Macrophytes		Derived from the literature, field observations and laboratory experiments, as appropriate.
Max Macrophyte Growth Rate Constant	Mphy Max Gro Const	
TP Concentration of Macrophyte Biomass	Mphy TP gmPkgB	
Min Areal TP Conc in Macrophytes	Mphy TP Min gBpa	
Max Areal Macrophyte Biomass	Mphy Mass Max kgBpa	
Fraction of Macrophytes becoming Detritus	Mphy Detri Fract	
Fraction Macrophyte P Uptake from Water	Mphy Water Upt Fract	
Periphytion Erosion vs Velocity	Mphy Erosion Coeff	
Macrophyte Slough Rate Constant	Mphy Slough Const	
9. Inputs Defining P Processing within Detritus		Derived from the literature, field observations and laboratory experiments, as appropriate.
Detrital P Decay Rate Constant	Detri Decay Const	
Fraction of Particulate P Settling in Reach	Settle Fract Const	
Detritus Erosion vs Velocity	Detritus Erosion Coeff	

The second category (Inputs Defining Stream Channel) are those inputs that define the hydraulics of the stream flow through the reach, define the average characteristics of the sediments on the stream reach bottom, and define the area of periphyton and macrophyte habitat in the reach. Different values of these inputs define stream reaches having different characteristics . For example, values may be entered to indicate that the reach is fast flowing (as in a riffle) or slow flowing (as in a backwater area). The stream bottom may contain much sediment and be largely inhabited with macrophyte beds or be cobbly with few macrophytes and contain large areas colonized by epilithon. By entering selected values into the parameters in this second category it is, thus, possible to simulate P processing and transport in and through stream reaches of very diverse characteristics.

The third category (Input Defining Initial Conditions) are those inputs that characterize the initial conditions of periphyton, macrophyte and detrital TP mass at the time the simulation run is initiated. These initial values reflect the specific conditions in a particular stream reach and also the time of year. For the purposes of this report, all simulation runs made with the initial version of the DSPM are started with the values of the inputs in this category set to the numerical values shown in Table 2.4.

The fourth category (Inputs Defining Time of Year of Simulation) are those inputs that set the initial Julian date of the simulation run and that define how rates of growth, diffusion and sloughing vary over the annual cycle. The particular relationships provided with this initial version of the DSPM are approximations of how the growth and sloughing of periphyton and macrophytes might vary in the Lake Champlain basin over a typical annual cycle (see Table 2.5). Another relationship in this category defines the variation in the rate of P diffusion from summer to winter due to changes in the water temperature.

The remaining five categories contain the inputs that define how P is transformed within and among the various P compartments. The required inputs in these categories are derived from various theories of how P is processed as reported in the literature. For example, the inputs listed in category five (Inputs Defining P Adsorption/Desorption) are those required to define the Langmuir Isotherm and to describe diffusion in accordance with Fick's First Law of Diffusion. The numerical values entered into these inputs are determined either by field measurement, by laboratory experiment or are extracted from the literature. The same is true for categories 6 through 9. The numerical values for the input parameters included in categories 5 - 9, as used in this project, are given in Table 2.6.

Table 2.4 Summary of input data requirements that define initial conditions for the DSPM. Numerical values of the parameters listed in this table are required to define the initial conditions of each simulation run. The user may wish to modify these values to reflect more appropriate initial conditions for specific summer or winter simulations.

INPUT PARAMETERS

DSPM Model Variable Names	Numerical Value	Units
TP Algal Init mgPpgB	4	mg/P/gm dry biomass
Algal Mass Init gBpa	50	gm dry mass/m^2
Mphy Mass Init kgBpa	0.03	kg dry biomass/m^2
Detri Mass Init kgPpa	6×10^{-6}	kg P/m^2
TP Sed Init gPkgS	0.35	gm P/kg dry sediment

Input Parameters for Defining Stream Reaches

DSPM Input Parameter	Units	Parameter Value	
		Spear Street	Bacon Drive
Length of Reach m	meters	150	150
Depth Flow vs Q	see relationship in Appendix D		
Avg Vel vs Q	see relationship in Appendix D		
Hyd Rad vs Q	see relationship in Appendix D		
Chan slope	dimensionless	0.0085	0.0025
Width @ LowQm	meters	11.5	14.5
Sed Part Dia mm	millimeters	0.50	0.25
Sed Bulk Den	gram/cu. cm	1.75	1.75
Sed Area Fract	dimensionless	0.07	0.50
Epil Hab Area Fract	dimensionless	0.75	0.35
Mphy Hab Area Fract	dimensionless	0.025	0.825
Sed Init Depth	centimeters	5	5
Wt Fract Fines	dimensionless	0.03	0.10

Table 2.5 Summary of seasonal adjustment factors. Days in **bold** type represent the warm water, high light intensity, growing period. The days in *italics* are the cold water, low light, winter period of little or no growth. The remaining periods, April and September, are the spring emergence and the fall senescence periods, respectively.

Day of Year	Approx. day/ Month	Algal Gro Adj	Mphy Gro Adj	Mphy Slough Adj	Detritus Decay Adj	Adsorb Adj
1	*1 Jan*	*0.02*	*0.00*	*10.00*	*0.10*	*0.70*
15		*0.02*	*0.00*	*10.00*	*0.10*	*0.70*
30	*1 Feb*	*0.03*	*0.00*	*10.00*	*0.10*	*0.70*
46		*0.05*	*0.00*	*10.00*	*0.10*	*0.70*
61	*1 Mar*	*0.10*	*0.00*	*10.00*	*0.10*	*0.72*
76		*0.25*	*0.00*	*8.00*	*0.10*	*0.74*
91	1 Apr	0.50	0.00	4.00	0.20	0.77
106		0.70	0.04	2.00	0.86	0.88
122	1 May	0.85	0.10	1.00	1.00	0.93
137		**0.95**	**0.80**	**1.00**	**1.00**	**0.99**
152	**1 June**	**1.00**	**0.97**	**1.00**	**1.00**	**1.00**
167		**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
183	**1 July**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
198		**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
213	**1 Aug**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
228		**1.00**	**1.00**	**2.00**	**1.00**	**1.00**
243	1 Sept	1.00	0.00	4.00	1.00	1.00
259		0.95	0.00	8.00	0.79	0.98
274	1 Oct	0.85	0.00	10.00	0.40	0.90
289		*0.70*	*0.00*	*10.00*	*0.19*	*0.80*
304	*1 Nov*	*0.50*	*0.00*	*10.00*	*0.10*	*0.74*
319		*0.25*	*0.00*	*10.00*	*0.10*	*0.70*
335	*1 Dec*	*0.14*	*0.00*	*10.00*	*0.10*	*0.70*
350		*0.06*	*0.00*	*10.00*	*0.10*	*0.70*
365	*31 Dec*	*0.02*	*0.00*	*10.00*	*0.10*	*0.70*

Table 2.6 Numerical values for data inputs categories 5 - 9. Numerical values of the parameters listed in this table are required to define the conditions for each simulation.

DSPM Model Variable Names	Numerical Value	Units
Inputs Defining P Adsorption/Desorption		
Ads Max Cap Sed	0.25	gm P/kg dry Sediment
Ads Affin K	1000	liters/gm P
Diff BL Thick cm	1	cm
Diff Const	0.001	cm^2sec
Inputs Defining P Processing By Periphyton		
Algal mu max	0.015	1/hr
P rho Max	0.1	mg P/gm dry biomass/hr
Km P	0.05	mg BAP/l
Ks 05μ	1	mg TP/gm dry biomass
TP Algal Max mgPgB	8	mg TP/gm dry biomass
TP Algal Min mgPgB	0.6	mg TP/gm dry biomass
Algal Mass Max gBpa	100	gm dry biomass/m^2
Algal Mass Min gBpa	5	gm dry biomass/m^2
PerCent Ash Pphy	80	dimensionless
Leak Rate Const	0.0001	1/hr
Pphy Slough Const	0.0001	1/hr
Pphy Erosion Coeff	See relationship*	dimensionless
Pphy Detach Fract	0.7	dimensionless
Inputs Defining P Transport by Sediments		
Kin Visc Water	1.007×10^{-6}	m^2/sec
Spec Grav Sed	2.65	dimensionless
Spec Grav Water	1	dimensionless
Bedload Ref Conc	10	mg Dry Sediment/l
VonKarmen Const	0.4	dimensionless
Grav Const	9.8	m/sec^2
Inputs Defining P Processing by Macrophytes		
Mphy Max Gro Const	0.0025	1/hr
Mphy TP gmPkgB	3.2	gm P/kg dry biomass
Mphy TP Min kgPpa	0.000008	kg P/m^2 habitat
Mphy Mass Max kgBpa	0.2	kg dry biomass/m^2
Mphy Detri Fract	0.5	dimensionless
Mphy Water Upt Fract	0.7	dimensionless
Mphy Erosion Coeff	See relationship*	dimensionless
Mphy Slough Const	0.0005	1/hr
Inputs Defining P Processing within Detritus		
Detri Decay Const	0.0008	1/hr
Settle Fract Const	0.01	dimensionless
Detritus Erosion Coeff	See relationship*	dimensionless

* these input relationships are functions of other variables. See code in Appendix B.

RESULTS

3.1 STOCK ASSESSMENT

3.1.1 Water

Concentrations of TP, SRP, and TDP determined during stock assessments are shown in Table 3.1. The stock (mg/m^2) of SRP and TP in the water compartment was calculated for each assessment date as the product of concentration and estimated water volume within each reach. The flux (kg/day) of SRP and TP from each reach was also estimated for each assessment date, as the product of measured SRP or TP concentrations and discharge. For the Bacon Dr. site, stream discharge was assumed to be equal to that measured at the USGS Shelburne Falls gaging station just downstream; discharge at the Spear St. site was estimated as 66% of the USGS discharge, based on the relative proportion of the contributing watershed area at Spear St.. Water volume was estimated from measurements of reach width and water depth made during stock assessments. Reach length was assumed to be 150 m at all times.

Stock and flux estimates for each assessment date are shown for Spear St. and Bacon Dr. in Tables 3.2 and 3.3, respectively. Stock estimates are plotted in Figures 3.1 and 3.2. At Spear St., TP stock varied between 8 and 34 mg/m^2; stocks tended to be highest in summer and lowest in winter and spring. Stocks of SRP were somewhat lower, generally less than 20 mg/m^2, with a seasonal pattern similar to that of TP. Concentrations of SRP averaged 50-60% of TP concentrations; as a result, a substantial proportion of TP stocks was consistently made up of SRP. This is at least in part the result of sampling at relatively low streamflows, when suspended solids levels were probably low.

Table 3.1 Phosphorus concentrations (mg/L) in water at stock assessments.

Date	P Form	SPEAR ST. Up[1]	SPEAR ST. Down[2]	BACON DR. Up	BACON DR. Down
10/25/93	TP	0.06	0.06	0.06	0.06
	SRP	0.05	0.05	0.06	0.06
1/25/94	TP	0.08	0.08	0.13	0.07
	SRP	0.03	0.03	0.03	0.03
5/23/94	TP	0.06	0.06	0.06	0.06
	SRP	0.02	0.02	0.02	0.02
8/ 2/94	TP	0.14	0.13	0.12	0.12
	SRP	0.10	0.10	0.09	0.09
8/ 8/94[3]	TP	0.19	0.18	--	0.16
	SRP	--	--	--	--
10/ 3/94	TP	0.08	0.08	0.06	0.06
	SRP	0.06	0.06	0.05	0.05
2/16/95	TP	0.05	0.05	0.04	0.04
	SRP	0.02	0.02	0.02	0.02
4/11/95	TP	0.03	0.03	0.02	0.02
	TDP	0.02	0.02	0.01	0.01
	SRP	0.01	0.01	0.01	0.01

1 "Up" denotes upstream end of reach.
2 "Down" denotes downstream end of reach.
3 Special post-high flow sampling.

Table 3.2 Reach characteristics and water total phosphorus(TP) and soluble reactive phosphorus (SRP) concentrations, stocks, and fluxes, in the Spear St. reach.at seasonal stock assessments.

Date	Q (ft3/sec)	[TP] (mg/l)	mean depth (m)	mean width (m)	Vol (m3)	TP STOCK		TP FLUX	
						(g)	(mg/m2)	(g/sec)	(kg/day)
25 Oct 93	14	0.06	0.335	11.5	577.9	34.67	20	0.024	2.1
25 Jan 94	9	0.08	0.2	10	300.0	24.00	16	0.020	1.8
23 May 94	23	0.06	0.24	10.1	363.6	21.82	14	0.039	3.4
2 Aug 94	6	0.14	0.24	9.2	331.2	46.37	34	0.024	2.1
8 Aug 94	7	0.18	0.168	9.2	231.8	41.73	30	0.036	3.1
3 Oct 94	4	0.08	0.15	8.6	193.5	15.48	12	0.009	0.8
16 Feb 95	14	0.05	0.22	11	363.0	18.15	11	0.020	1.7
11 April 95	11	0.03	0.278	10.2	425.3	12.76	8	0.009	0.8

Date	Q (ft3/sec)	[SRP] (mg/l)	mean depth (m)	mean width (m)	Vol (m3)	SRP STOCK		SRP FLUX	
						(g)	(mg/m2)	(g/sec)	(kg/day)
25 Oct 93	14	0.05	0.335	11.5	577.9	28.89	17	0.020	1.7
25 Jan 94	9	0.03	0.2	10	300.0	9.00	6	0.008	0.7
23 May 94	23	0.02	0.24	10.1	363.6	7.27	5	0.013	1.1
2 Aug 94	6	0.1	0.24	9.2	331.2	33.12	24	0.017	1.5
8 Aug 94	7	---	0.168	9.2	231.8	---	---	---	---
3 Oct 94	4	0.06	0.15	8.6	193.5	11.61	9	0.007	0.6
16 Feb 95	14	0.02	0.22	11	363.0	7.26	4	0.008	0.7
11 April 95	11	0.01	0.278	10.2	425.3	4.25	3	0.003	0.3

Table 3.3 Reach characteristics and water total phosphorus(TP) and soluble reactive phosphorus (SRP) concentrations, stocks, and fluxes, in the Bacon Dr. reach.at seasonal stock assessments.

Date	Q (ft3/sec)	[TP] (mg/l)	mean depth (m)	mean width (m)	Vol (m3)	TP STOCK		TP FLUX	
						(g)	(mg/m2)	(g/sec)	(kg/day)
25 Oct 93	21	0.06	0.383	14.6	838.8	50.3	23.000	0.036	3.083
25 Jan 94	13	0.07	0.32	11	528.0	37.0	22.000	0.026	2.227
23 May 94	26	0.06	0.36	14.1	761.4	45.7	22.000	0.044	3.817
2 Aug 94	8.7	0.12	0.353	13	688.4	82.6	42.000	0.030	2.555
8 Aug 94	10	0.16	0.35	12	630.0	100.8	56.000	0.045	3.915
3 Oct 94	5.5	0.06	0.25	12.3	461.3	27.7	15.000	0.009	0.807
16 Feb 95	21	0.04	0.3	14	630.0	25.2	12.000	0.024	2.055
11 April 95	17	0.02	0.344	11.8	608.9	12.2	7.000	0.010	0.832

Date	Q (ft3/sec)	[TP] (mg/l)	mean depth (m)	mean width (m)	Vol (m3)	SRP STOCK		SRP FLUX	
						(g)	(mg/m2)	(g/sec)	(kg/day)
25 Oct 93	21	0.06	0.383	14.6	838.8	50.3	23.000	0.036	3.083
25 Jan 94	13	0.03	0.32	11	528.0	15.8	10.000	0.011	0.954
23 May 94	26	0.02	0.36	14.1	761.4	15.2	7.000	0.015	1.272
2 Aug 94	8.7	0.09	0.353	13	688.4	62.0	32.000	0.022	1.916
8 Aug 94	10	---	0.35	12	630.0	---	---	---	---
3 Oct 94	5.5	0.05	0.25	12.3	461.3	23.1	13.000	0.008	0.673
16 Feb 95	21	0.02	0.3	14	630.0	12.6	6.000	0.012	1.028
11 April 95	17	0.01	0.344	11.8	608.9	6.1	3.000	0.005	0.416

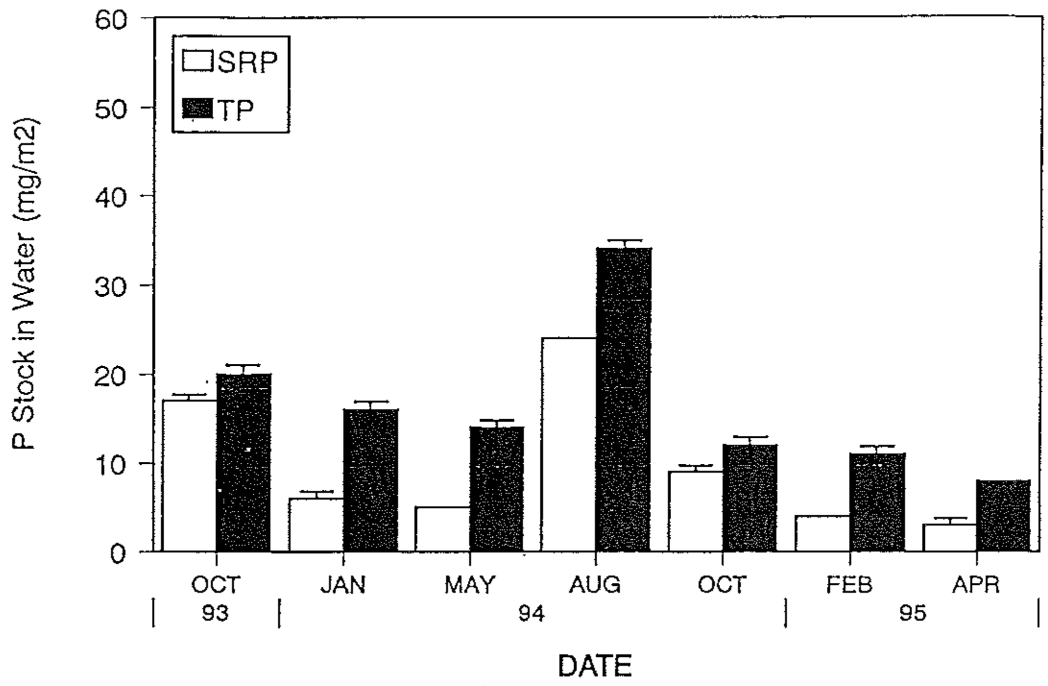


Figure 3.1 Total phosphorus (TP) and soluble reactive phosphorus (SRP) stocks in water, Spear St. reach, Error bars represent +1 standard error.

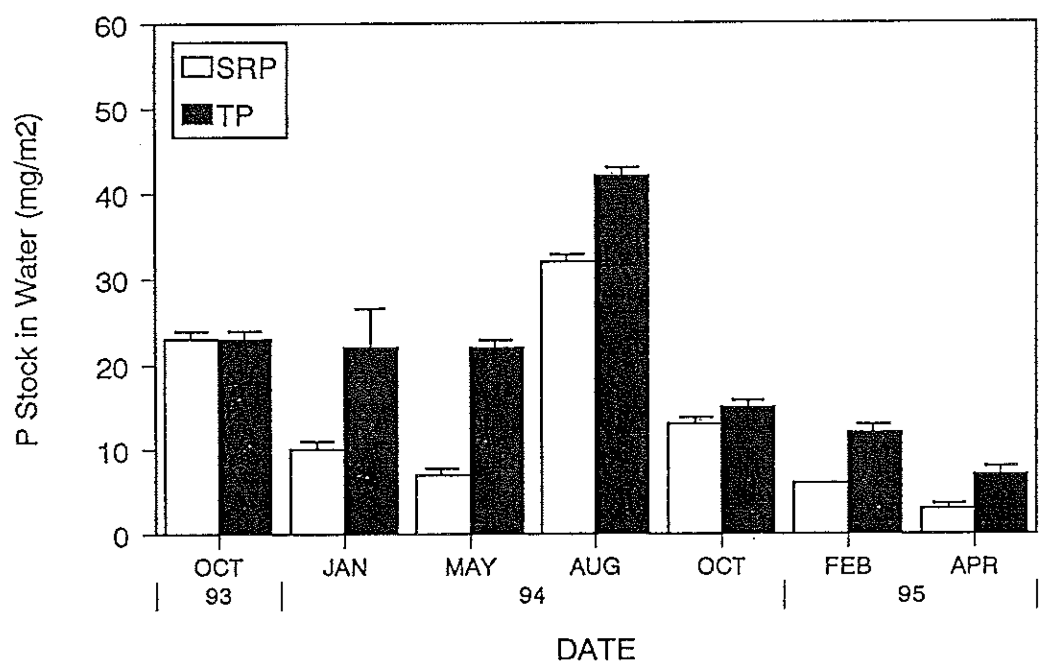


Figure 3.2 Total phosphorus (TP) and soluble reactive phosphorus (SRP) stocks in water, Bacon Dr. reach. Error bars represent +1 standard error.

P stocks in the water compartment at Bacon Dr. tended to be higher than those at Spear St., primarily due to the larger water volume. Stocks of TP ranged from 7 to 56 mg/m^2, with the highest values measured in summer and the lowest in winter and spring, as at Spear St. SRP stocks ranged from less than 3 to 32 mg/m^2 and followed the same seasonal pattern as TP.

Phosphorus flux on each assessment date is plotted in Figures 3.3 and 3.4. Fluxes were, of course, primarily driven by discharge. Total P flux from the Spear St. reach ranged from 0.8 to 3.4 kg/day , and from Bacon Dr. from 0.8 to 3.9 kg/day. SRP fluxes were about 0.3 to 1.7 kg/day from Spear St. and 0.4 to 3.0 kg/day from Bacon Dr. These flux values are fairly low compared to average daily flux over an entire year because stock assessments were conducted at relatively low flows (see Figure 2.4). Based on monitored loads from the entire LaPlatte River basin, average TP flux is almost 40 kg/day (VT DEC and NYS DEC, 1994).

3.1.2 Sediment

A total of 234 samples were collected from August 1993 to April 1995 at the Spear St. and Bacon Dr. reaches. As discussed in Section 2.2.2.2, all of the Bacon Dr. samples (117 total) were subsectioned according to depth, generally yielding three intervals: 0-2 cm, 2-5 cm, and 5-8 cm. Because the dynamic simulation model assumes an active sediment depth of only 5 cm, and because statistical analysis revealed no significant differences between the 2-5 cm interval and the 5-8 cm interval, data are reported only for the upper two intervals. Data for the 5-8 cm layer will be published by Brown. Because Spear St. samples were bulk grab samples rather than cores, they were not subsectioned by depth but rather split into three different particle size intervals as described in Section 2.2.2.2, with sand and silts+clays analyzed separately. Particles larger than sand were not analyzed

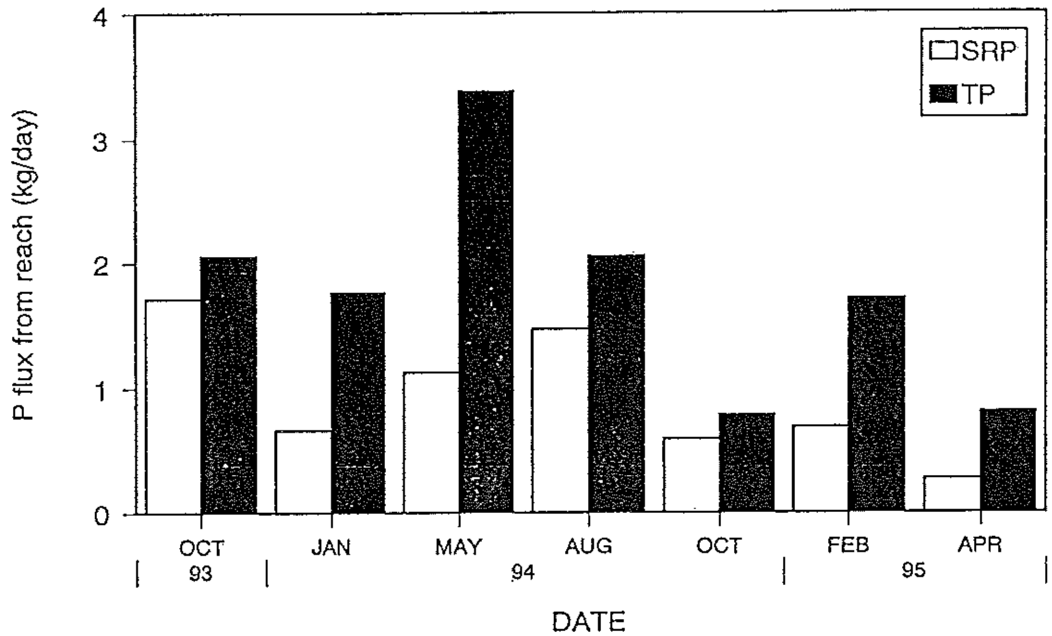


Figure 3.3 Total phosphorus (TP) and soluble reactive phosphorus (SRP) flux from Spear St. reach during seasonal stock assessments

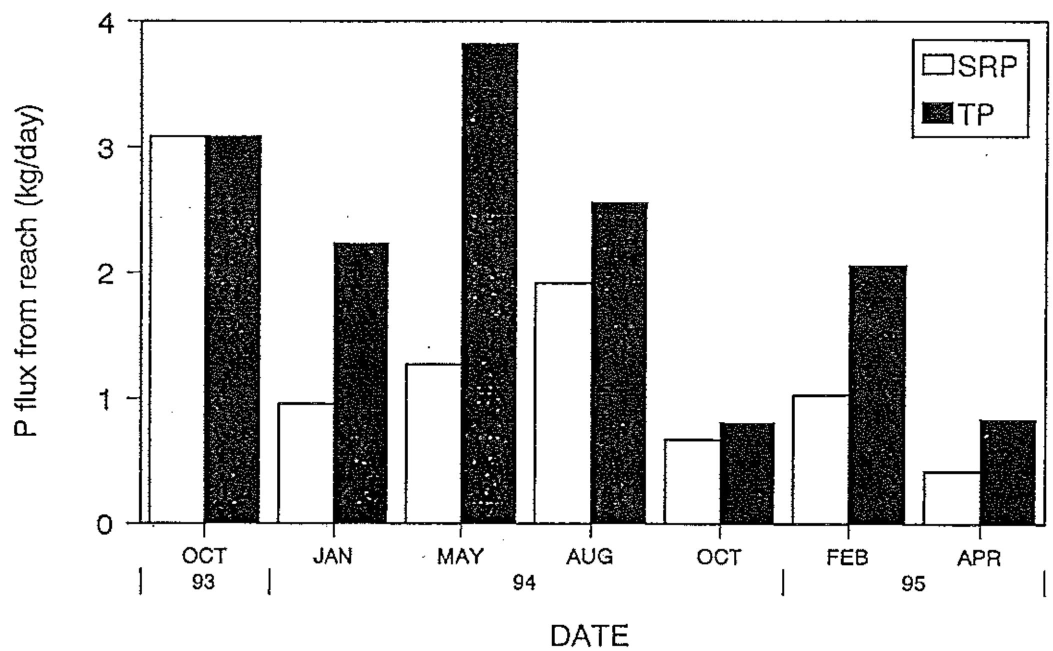


Figure 3.4 Total phosphorus (TP) and soluble reactive phosphorus (SRP) flux from Bacon Dr. reach during seasonal stock assessments

because it was assumed that: a) they would contain little phosphorus, and b) what phosphorus that was associated with the larger particles was probably present as epilithon. Nevertheless, the mass of sediments gravel sized and larger <u>has</u> been included in the calculation of mass of P per unit area of total sediment. At both sites, in addition to TP analysis, samples were collected along specific transects for grain size and TP analysis, and 40 samples were extracted to determine the amount of NaOH-P and HCl-P (see Section 2.2.2.2). The following results pertain only to TP and grain size. Although all analyses yielded TP concentrations as mg P/g dry sediment, sediment densities, volumes, and size distributions permit recasting this information as mg P/cm^3 (mass/unit volume) and as mass per unit area (mg P/m^2) <u>if</u> a specific depth of interaction is assumed.

At Spear St., material interstitial to cobbles and boulders constituted approximately 25-30% of the total streambed (estimated by point counting within the stream reach, Section 2.2.1.2). In calculating the mass per unit area and mass contained within the stream reach, a 28% coverage was assumed. The grain size distribution is indicated in Figure 3.5. The concentration of TP in the sand and silt+clay fractions, the calculated concentration of TP in bulk sediment samples, and total mass of TP per unit area (assuming a 5 cm depth) are given in Table 3.4. The concentration of TP in the fine component of the sediments (1.98 mg P/g) was approximately five times greater than in the sands (0.38 mg P/g), but because the coarser material was present in far greater amounts, the average concentration in bulk Spear St. sediments including particles larger than 2 mm was only 0.12 mg P/g. When the 0.12 mg P/g dry sediment concentration was extrapolated to an areal basis, the Spear St. reach contained slightly more than 2 g P/m^2 assuming a 28% coverage. Figures 3.5 and 3.6 summarize these data. ANOVA indicated no significant differences ($p = 0.95$) among sample dates (i.e. season) with respect to either grain size distribution or TP concentrations.

Table 3.4 Spear St. sediment size and composition (total phosphorus (TP) as mg TP/gm dry sediment; mg TP/m^2 has been calculated assuming 28% by area interstitial material including gravel component).

	mg TP/ g dry sed		mg TP/ g dry sed			
Season	Sands	Std. Err	Fines	Std. Err	mg TP/ M2	Std. Err
Fall 93	0.34	0.02	2.82	1.11	2536	364
Winter 94	0.37	0.04	2.15	0.28	1596	247
Spring 94	0.45	0.09	1.40	0.11	2510	574
Summer 94	0.34	0.02	1.53	0.13	1612	208
Fall 94	0.47	0.08	2.48	0.56	2895	443
Winter 95	0.36	0.04	1.69	0.10	1963	390
Spring 95	0.31	0.04	1.76	0.44	2421	296
Average	0.38	0.05	1.98	0.39	2219	360
Season	% Gravel	Std err	% Sand	Std err	%Silt + Clay	Std err
Fall 93	60.18%	6.34%	39.16%	6.34%	0.33%	0.17%
Winter 94	74.39%	3.85%	24.17%	3.45%	1.47%	1.11%
Spring 94	74.74%	4.08%	24.86%	4.11%	0.45%	0.18%
Summer 94	78.94%	3.46%	20.39%	3.65%	0.65%	0.21%
Fall 94	75.34%	3.17%	23.80%	3.15%	0.86%	0.11%
Winter 95	74.54%	5.43%	24.05%	4.85%	1.41%	1.03%
Spring 95	68.55%	4.11%	30.88%	4.03%	0.58%	0.09%
Average	72.38%	4.35%	26.76%	4.23%	0.82%	0.41%

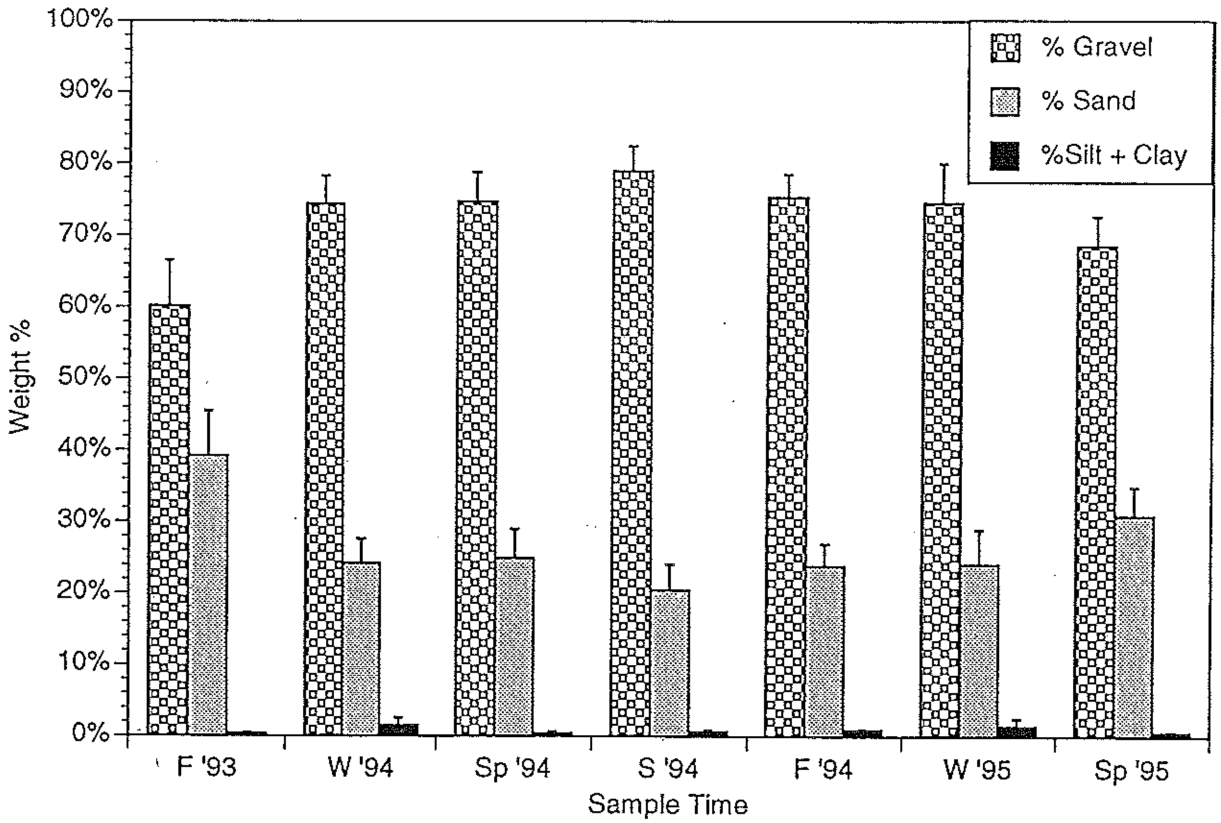


Figure 3.5 Average sediment composition at Spear St.; grain size as weight percent.

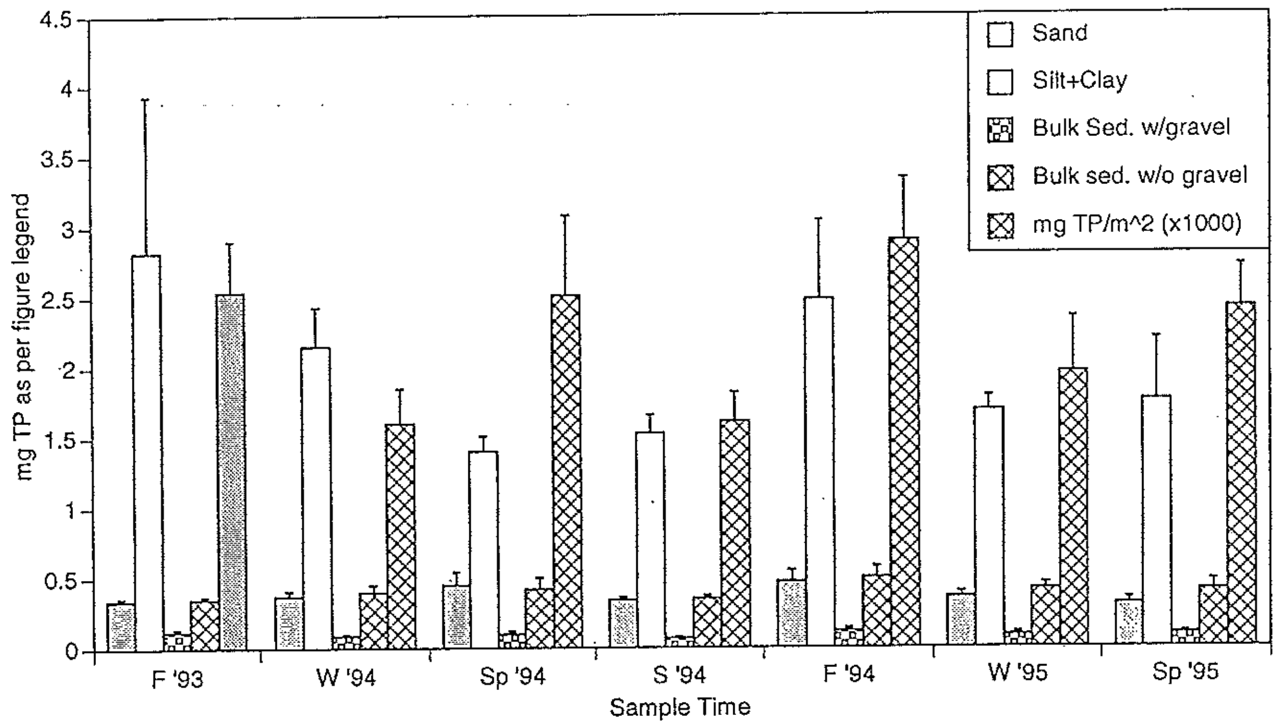


Figure 3.6 Spear St. average sediment composition: TP concentration in the sand and silt+clay fractions as mg P/g dry sediment; aggregate sample TP (bulk sed.) including and excluding the greater than 2 mm fraction as mg P/g dry sediment: and mass of TP including the greater than 2 mm fraction as mg TP/m^2 times 1000.

Table 3.5 Grain size and composition of Spear St. transect samples.

Transect			Grain Size %		mg P/ g dry sed	mg P/ g dry sed	per 0-5cm
Station	Season	% Gravel	% Sand	%Silt + Clay	Sands	Fines	mg P/ M^2
T1	Spring 1994	67.44%	31.22%	1.34%	0.29	1.54	2466
	Summer 1994	58.50%	40.17%	1.33%	0.37	1.40	5657
	Summer 1994	75.61%	24.13%	0.26%	0.28	1.76	1887
	Fall 1994	60.49%	38.39%	1.12%	0.26	4.90	3451
		% Gravel	% Sand	%Silt + Clay	Sands	Fines	mg P/ M^2
T2	Spring 1994	93.09%	6.84%	0.07%	0.26	1.52	425
	Summer 1994	68.27%	31.73%	2.12%	0.28	1.59	3254
	Summer 1994	70.91%	28.03%	1.06%	0.37	6.54	4763
	Fall 1994	72.91%	26.43%	0.66%	0.34	2.04	2530
	Winter 1995	95.77%	4.11%	0.12%	0.40	1.54	629
	Spring 1995	74.95%	23.97%	1.08%	1.60	1.28	10378
		% Gravel	% Sand	%Silt + Clay	Sands	Fines	mg P/ M^2
T3	Spring 1994	86.70%	13.08%	0.22%	0.28	1.19	991
	Summer 1994	76.40%	23.04%	0.56%	0.60	1.68	4142
	Summer 1994	85.34%	14.33%	0.33%	0.22	1.50	1125
	Fall 1994	64.77%	34.69%	0.55%	0.33	1.55	2700
	Spring 1995	52.19%	47.71%	0.11%	0.39	3.82	4402
		% Gravel	% Sand	%Silt + Clay	Sands	Fines	mg P/ M^2
T4	Spring 1994	62.99%	36.27%	0.74%	0.31	3.61	3484
	Spring 1995	74.93%	24.71%	0.35%	0.27	1.49	1602

In an attempt to ascertain variability at a specific site (not possible with the original random sampling design), four sampling stations were established along a transect in the Spear St. reach. The results of repeated sampling at these locations are shown in Table 3.5 (data for T2, Spring 1995 are questionable due to suspected contamination or analytical error.). Although data at any given station exhibit significant variability, there was no systematic trend in either grain size distribution or TP concentration from season to season or between stations.

A total of 117 samples from the Bacon Dr. reach were analyzed for TP. In addition, NaOH and HCl extractions were done on 15 of these samples and 14 transect samples were analyzed for grain size distribution. In general, samples were not subdivided by grain size, but were split into three depth intervals (0-1 cm, 2-5 cm, and >5 cm) with results from only the top two intervals reported here. Results of TP analyses and loss on ignition measurements are given in Table 3.6 and in Figures 3.7 and 3.8. These results indicate that there was little difference between the compositions of the two sediment layers and that the mass of TP contained within the sediment stock was approximately 5.5 g P/m^2 per cm interval throughout the reach. If this is adjusted for an estimated 33% coverage of the stream bottom by cobble, pebbles, and other such substrate, the "average" P content of the stream bottom is reduced to 3.6 g P/m^2 per cm depth interval. No significant differences between TP concentration or mass/area with regard to depth or season were observed by ANOVA.

In addition to random sampling, several stations located along pre-established transects were repeatedly sampled, and the results are presented in Table 3.7. Because of the relatively low sample numbers (generally 2 or 3) compiled for each average, these results are suggestive at best. In general, chemical properties of transect samples, such as loss on

Table 3.6 Loss on ignition (LOI) and composition of Bacon Dr. sediments.

Season	LOI wt%		mg P/g dry sed		mg P/cm3		mp TP/m^2	
	0-2cm	Std Err	0-2cm(mg TP/g	Std Err	0-2cm	Std Err	0-2cm(mg TP/m^2)	Std Err
Summer 93	2.61%	0.38%	0.70	0.06	0.45	0.06	7468	886
Fall 93	2.06%	0.43%	0.58	0.07	0.47	0.03	9343	672
Winter 94	2.02%	0.48%	0.49	0.08	0.69	0.20	15304	4951
Spring 94	1.59%	0.27%	0.55	0.06	0.77	0.09	16128	2000
Summer 94	2.85%	0.81%	0.59	0.05	0.61	0.05	12483	1624
Fall 94	1.87%	0.34%	0.53	0.04	0.70	0.06	14775	1579
Winter 95	0.86%	0.23%	0.70	0.04	0.98	0.03	13296	1525
Spring 95	1.50%	0.59%	0.45	0.07	0.65	0.10	10903	1073
Average	1.92%	0.44%	0.57	0.06	0.66	0.08	12463	1789
	2-5cm	Std Err	2-5cm(mg TP/g	Std Err	2-5cm	Std Err	2-5cm(mg TP/m^2)	Std Err
Summer 93	1.33	0.23%	0.48	0.06	0.56	0.06	16436	2017
Fall 93	1.35	0.28%	0.50	0.06	0.60	0.06	17135	1543
Winter 94	2.51	0.83%	0.54	0.10	0.64	0.08	20860	2598
Spring 94	1.70	0.49%	0.54	0.09	0.71	0.05	21023	1530
Summer 94	1.33	0.13%	0.47	0.05	0.64	0.06	17038	1863
Fall 94	1.66	0.44%	0.47	0.07	0.66	0.12	23482	4502
Winter 95	0.61	0.05%	0.56	0.19	0.84	0.20	23220	2089
Spring 95	1.52	0.68%	0.48	0.06	0.76	0.09	20522	1408
Average	1.50	0.39%	0.50	0.08	0.68	0.09	19965	2194

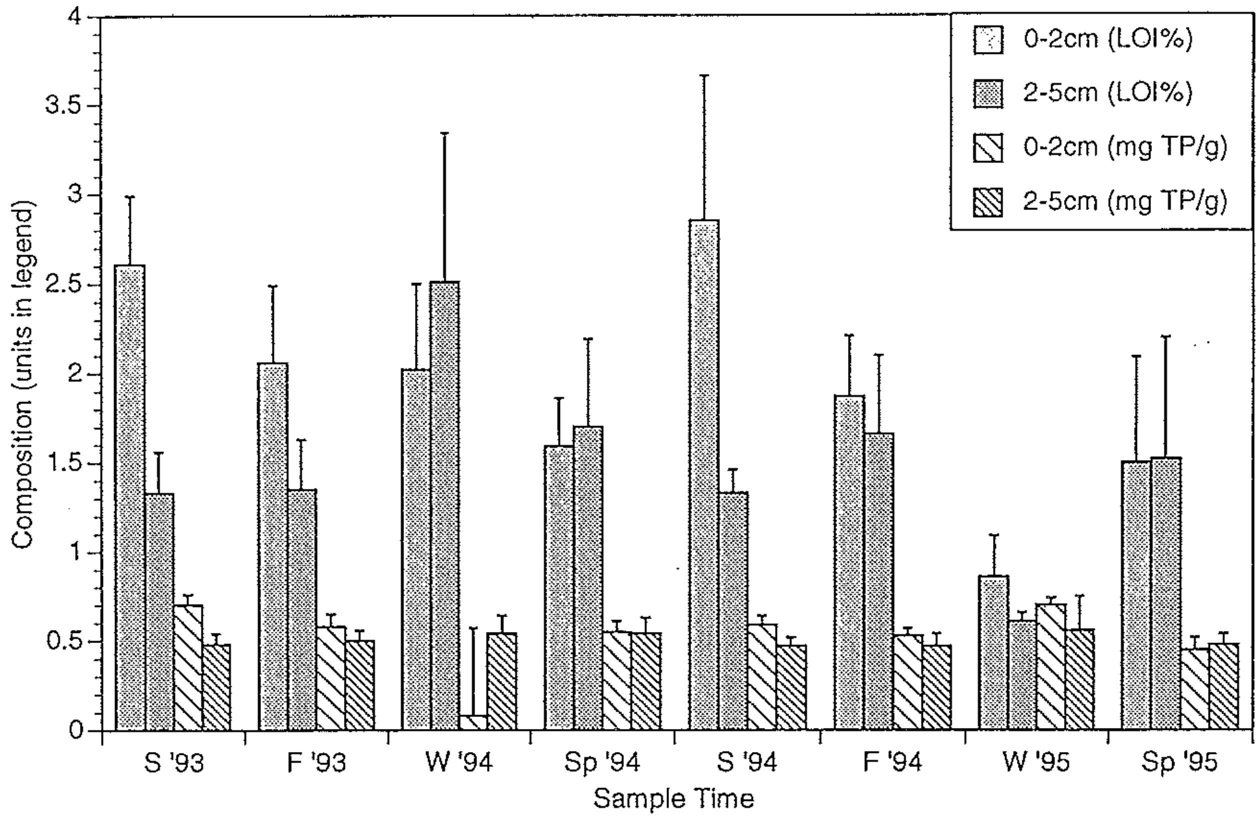


Figure 3.7 Bacon Dr. sediment composition for specific depth intervals; Loss on Ignition (LOI) as %, phosphorus concentration as mg P/g dry sediment excluding the greater than 2 mm fraction.

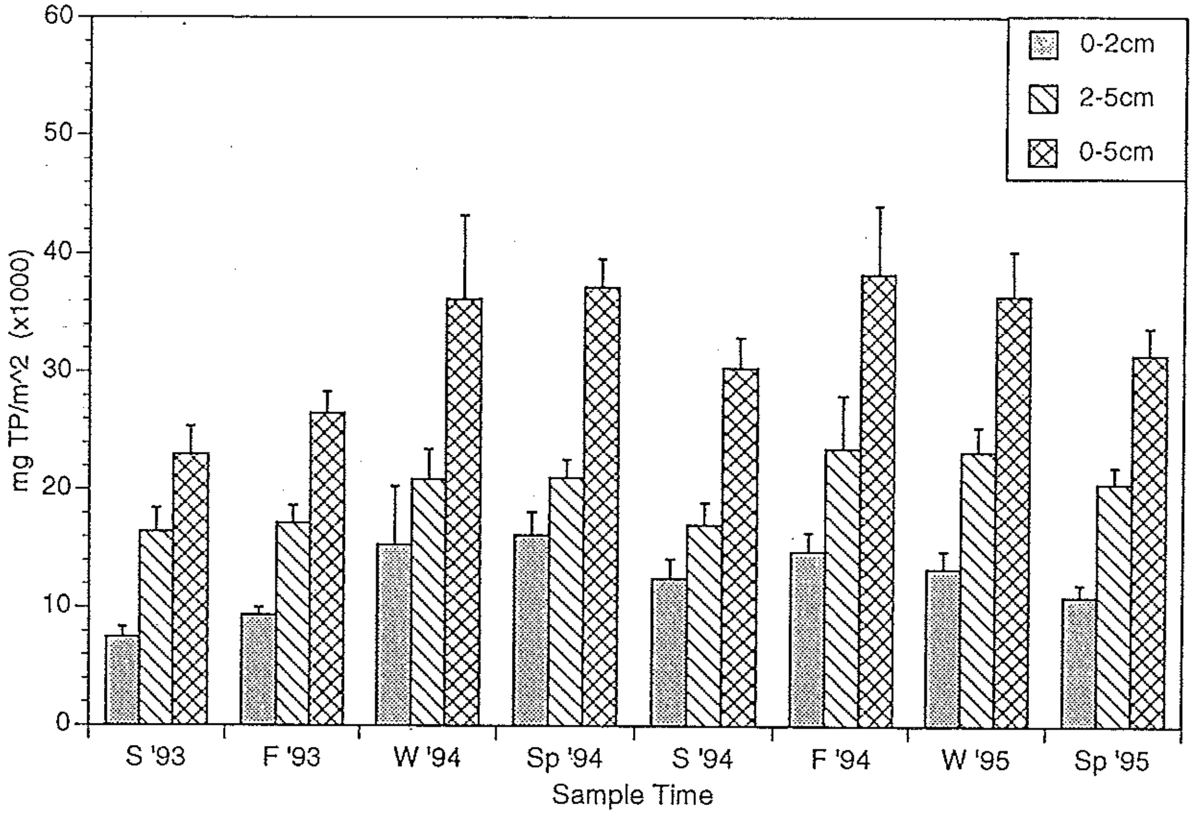


Figure 3.8 Sediment composition at Bacon Dr. for specific depth intervals. Mass TP per m^2 as mg P/m^2 including the greater than 2 mm fraction.

Table 3.7 Average composition of Bacon Dr. transect samples (S - 94* are post-storm samples; ** Averages and std error of all samples not of averages).

		Season						
	Interval	S-94	S-94*	F-94	W-95	Sp-95	Average**	Std. Error**
% Silt+clay	0-1 cm	3.8	5.4	25.9	8.1	3.7	10.9	5.7
	1-2 cm	2.0	4.5	23.6	16.2	3.2	11.6	5.4
	2-5 cm	6.3	2.4	23.7	11.2	2.6	4.2	10.9
% Sand	0-1 cm	72.1	77.3	42.9	84.3	88.2	70.2	9.4
	1-2 cm	74.1	76.0	45.5	68.0	84.5	67.5	8.8
	2-5 cm	66.8	84.4	55.4	65.7	67.7	66.8	7.1
% > Sand	0-1 cm	24.2	18.9	31.3	7.7	4.4	18.6	8.7
	1-2 cm	23.9	19.5	30.9	15.9	12.3	21.0	8.1
	2-5 cm	26.9	13.3	20.9	23.1	29.7	23.0	6.3
% LOI: silt+clay	0-1 cm	4.35	2.55	2.94	2.94	2.59	3.06	0.34
	1-2 cm	2.00	2.23	3.09	2.40	2.02	2.41	0.20
	2-5 cm	2.88	2.42	2.65	2.99	2.88	2.78	0.17
% LOI: sand	0-1 cm	0.40	0.55	1.38	0.68	0.56	0.77	0.22
	1-2 cm	0.49	0.46	2.12	0.60	0.41	0.91	0.37
	2-5 cm	0.43	0.44	1.21	0.60	0.46	0.65	0.19
mg TP/g dry fines	0-1 cm	1.12	1.18	1.31	1.14	2.53	1.44	0.27
	1-2 cm	1.05	1.03	1.17	1.05	0.58	1.00	0.08
	2-5 cm	1.00	1.14	1.11	0.97	2.11	1.21	0.18
mg TP/g sand	0-1 cm	0.23	0.40	0.38	0.30	0.31	0.33	0.02
	1-2 cm	0.45	0.31	0.40	0.42	0.26	0.37	0.04
	2-5 cm	0.33	0.32	0.32	0.35	0.24	0.32	0.02

ignition and TP concentrations in both sand and silt+clay fractions were relatively constant both spatially and temporally, whereas grain size distribution varied with respect to space and time, but with no discernable pattern, as indicated by the standard errors in Table 3.7.

3.1.3 Epilithon

Site and season both affected periphyton dry weight per unit area of rock substrate. Analysis of variance showed the main effects and interaction term to be significant ($p < 0.05$). Paired comparisons between the two sites within each 1994 season showed the spring and summer sampling dates to be significantly different ($p < 0.05$); whereas the fall and winter sampling dates were not. Dry weight was greater at Bacon Dr. in summer than in the spring, but it was less at Spear St. in summer than spring. Dry weight was highest at both sites in the fall and decreased in the winter (Figure 3.9). Over all seasons, with the exception of winter, dry weight was higher at Bacon Dr. When averaged over all seasons sampled in 1993, 1994 and 1995, epilithon dry weight (per m^2 of rock substrate) was greatest at Bacon Dr. In contrast, when scaled to the reach, dry weight was greatest at Spear St. (Table 3.8). The mean dry weight on rocks in June 1995 before release of the 1 kg P pulse was 186 ± 29 (1 SE) g/m^2 and 4 days later was 195 ± 47 (1 SE) g/m^2. This suggests an accumulation rate of about 2 $g/m^2/d$; however a t-test of the dry weights from these two samplings was insignificant ($p=0.86$) due to high variance.

Epilithon AFDM (Ash-Free Dry Matter, i.e. dry weight of organic matter) was greater at Spear St. whether scaled to the reach or expressed per unit area of substrate, while the P stock was comparable between both sites per unit area of substrate but was greater at Spear St.. when scaled to the reach (Table 3.8). Figures 3.10, 3.11, and 3.12 depict the arithmetic means of dry weight, AFDM and P stock for each site and each season sampled in 1993, 1994 and 1995 and clearly show the greater amount of AFDM present at

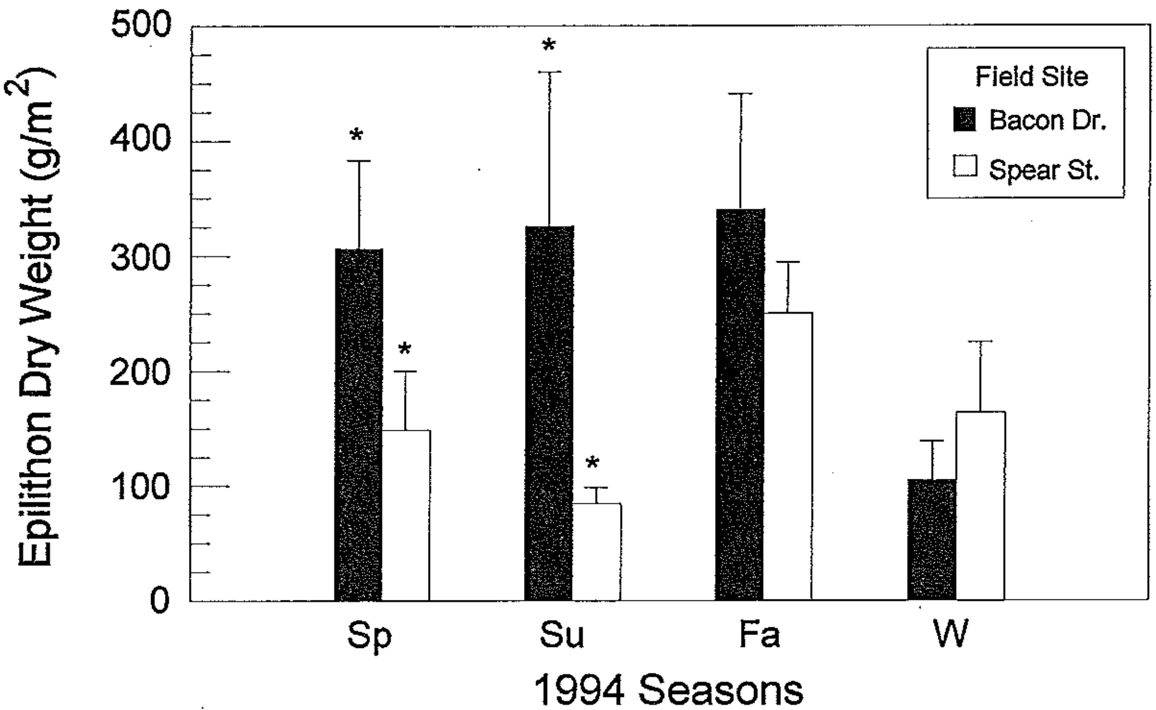


Figure 3.9 Geometric means of the epilithon dry weight for the 1994 seasons at Bacon Dr. and Spear St. sites (n-9 to 19, 1 SE shown). Bars marked with an asterisk indicate that the means for the two sites at that season are significantly different ($p<0.05$).

Table 3.8 Mean periphyton dry weight and calculated ash-free dry mass and P for Bacon Dr. and Spear St. sites averaged over all seasons sampled in 1993-1995. Values are in g/m^2(± 1 SE).

	Dry Weight	AFDM	Phosphorus
Bacon Dr.			
Substrate [a]	400.4 (± 49.6)	34.1 (± 4.3)	0.73 (± 0.23)
	(n = 56)		
Reach [b]	146.6 (± 23.9)	12.6 (± 1.6)	0.27 (± 0.09)
	(n = 153)		
Spear St.			
Substrate [a]	221.0 (± 20.3)	46.9 (± 4.5)	0.60 (± 0.10)
	(n = 155)		
Reach [b]	177.5 (± 17.7)	37.5 (± 3.6)	0.48 (± 0.08)
	(n = 193)		

[a] Values expressed per square meter of rock substrate.

[b] Values averaged over entire area of reach.

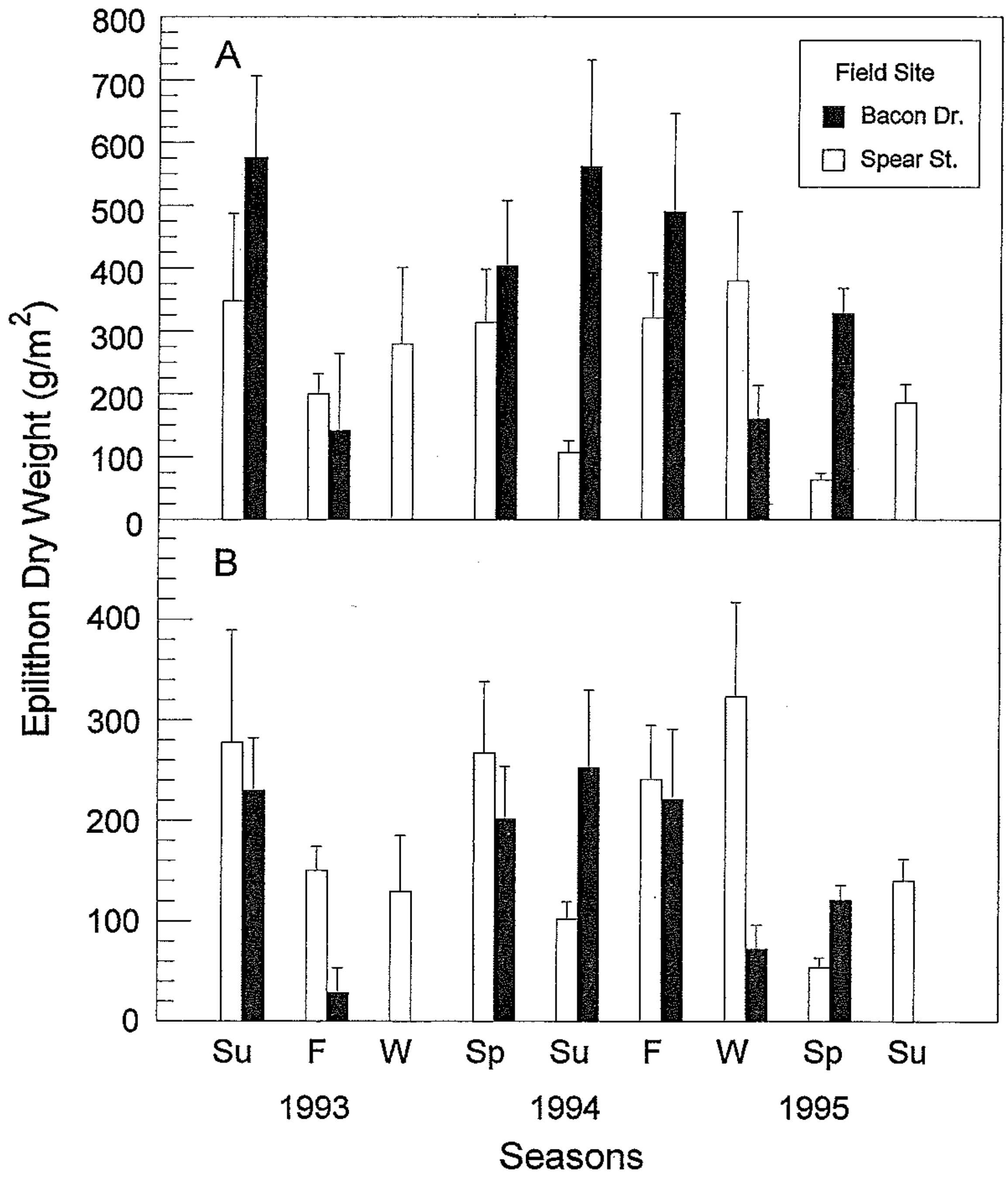


Figure 3.10 Means of epilithon dry weight for all seasons sampled at Bacon Dr. and Spear St. (A) Data normalized to a unit of rock surface; no zero values included (n=4 to 19, 1 SE shown). (B) Data normalized to a unit area of the 150 m long reach; zero values included (n=20, 1 SE shown).

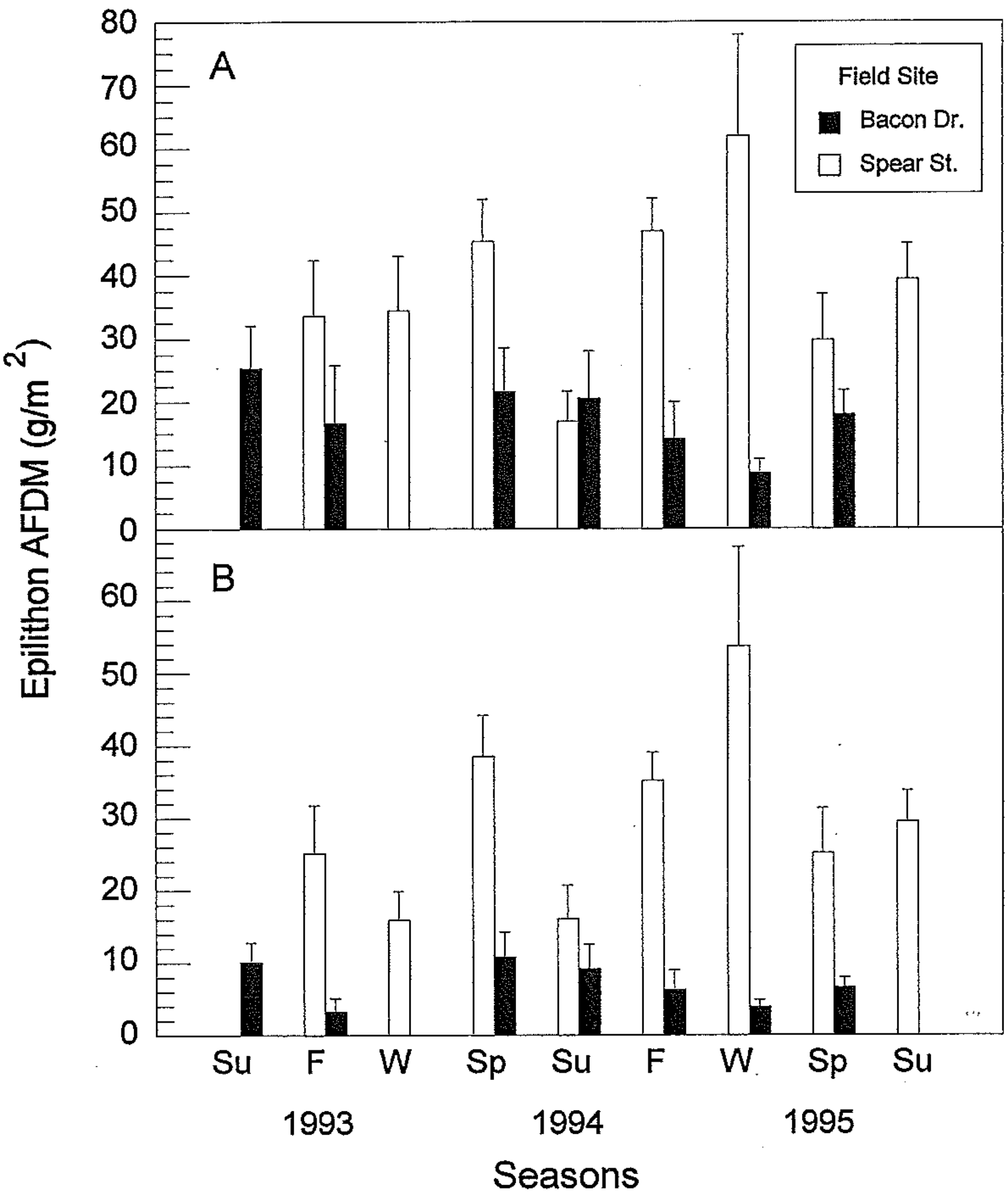


Figure 3.11 Derived means and standard errors of epilithon ash-free dry mass (AFDM) for all seasons sampled at Bacon Dr. and Spear St. (A) Data normalized to a unit area of rock surface. (B) Data normalized to a unit area of the 150 m long reach.

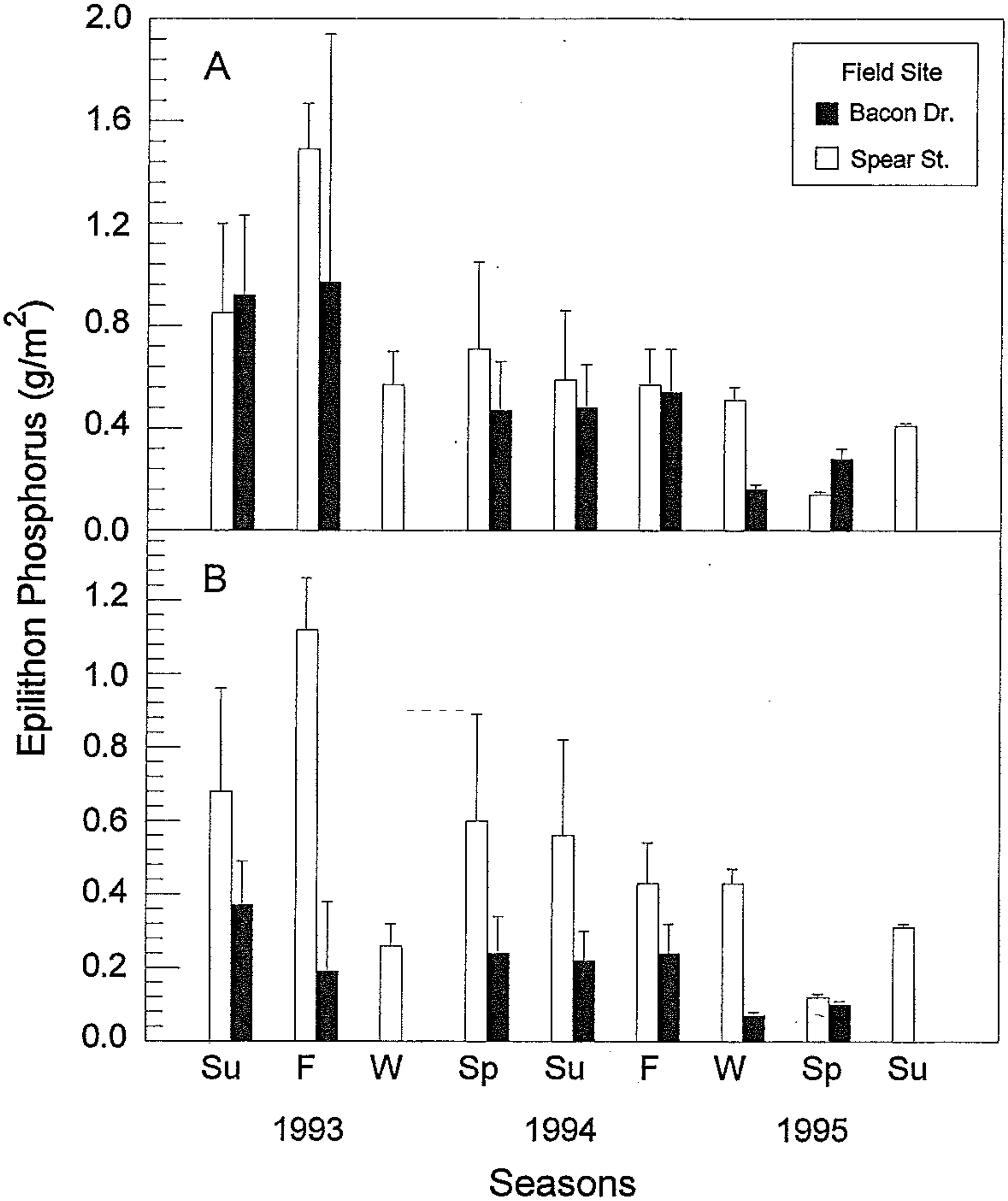


Figure 3.12 Derived means and standard errors of epilithon phosphorus stock for all seasons sampled at Bacon Dr. and Spear St. (A) Data normalized to a unit area of rock surface. (B) Data normalized to a unit area of the 150 m long reach.

Spear St., especially in the winter. Ash content was positively related to periphyton dry weight and was markedly higher at Bacon Dr. than Spear St. (Figure 3.13), whereas % P was inversely related to ash content and was generally higher at Spear St. (Figure 3.14). Epilithon P stock at Bacon Dr. increased with dry weight, while the P stock at Spear St. showed no apparent relationship to dry weight (Figure 3.15). Both dry weight and P stock increased with AFDM and appeared to increase more per unit increase in AFDM at Bacon Dr. than at Spear St. (Figures 3.16 and 3.17).

3.1.4 Macrophytes and Epiphytes

During the period of plant growth in Vermont streams, macrophyte biomass was consistently greater by two orders of magnitude at the slow-moving, soft bottomed Bacon Dr. reach than at the swifter, rocky bottomed Spear St. reach (Table 3.9, Figure 3.18). Epiphyte biomass was similar in magnitude to macrophyte biomass in 1994 (Table 3.10). In 1993, substantially less epiphyte than macrophyte biomass was measured, but this may have been due to the less efficient sampling method used (enclosing macrophytes in a net and waving them to dislodge epiphytes, versus placing cut plant stems in bottles and shaking vigorously). Even the more rigorous method did not remove all traces of algae. Phosphorus concentration in both macrophytes and epiphytes generally ranged from 3-5 mg P/g DW (Tables 3.9,3.10). For the two sites, macrophyte P concentrations were similar (Table 3.9). Therefore, between site differences in plant storage of P were driven mostly by site differences in biomass (Table 3.9).

Macrophytes are highly seasonal in their growth dynamics. Although one of the plant species common in the LaPlatte River, *Elodea canadensis*, can overwinter, little to no biomass was measured at either the Spear St. or the Bacon Dr. reach during the winters of 1994 and 1995 (it is possible that with a reduced sampling effort in winter, the *Elodea* beds were missed at Bacon Dr.). Plants first appeared in the stream in May. Thus our late May

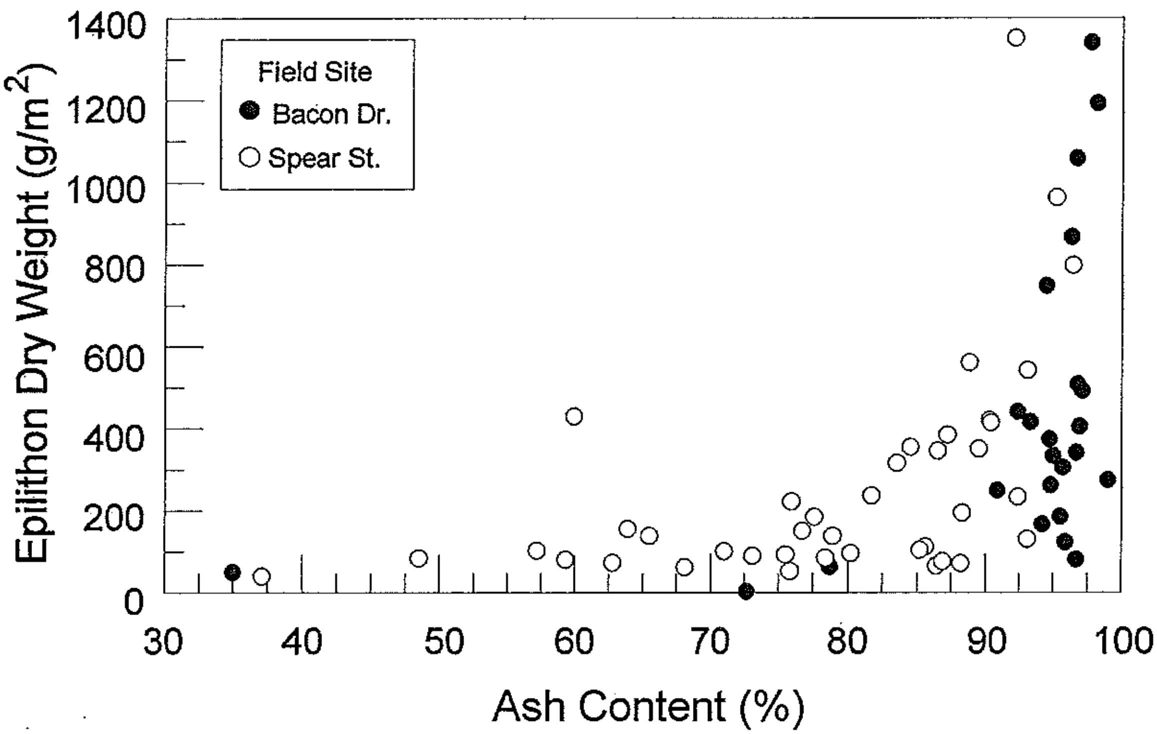


Figure 3.13 Relationship between epilithon dry weight, normalized to a unit area of rock surface, and % ash for those samples from all seasons that were ashed.

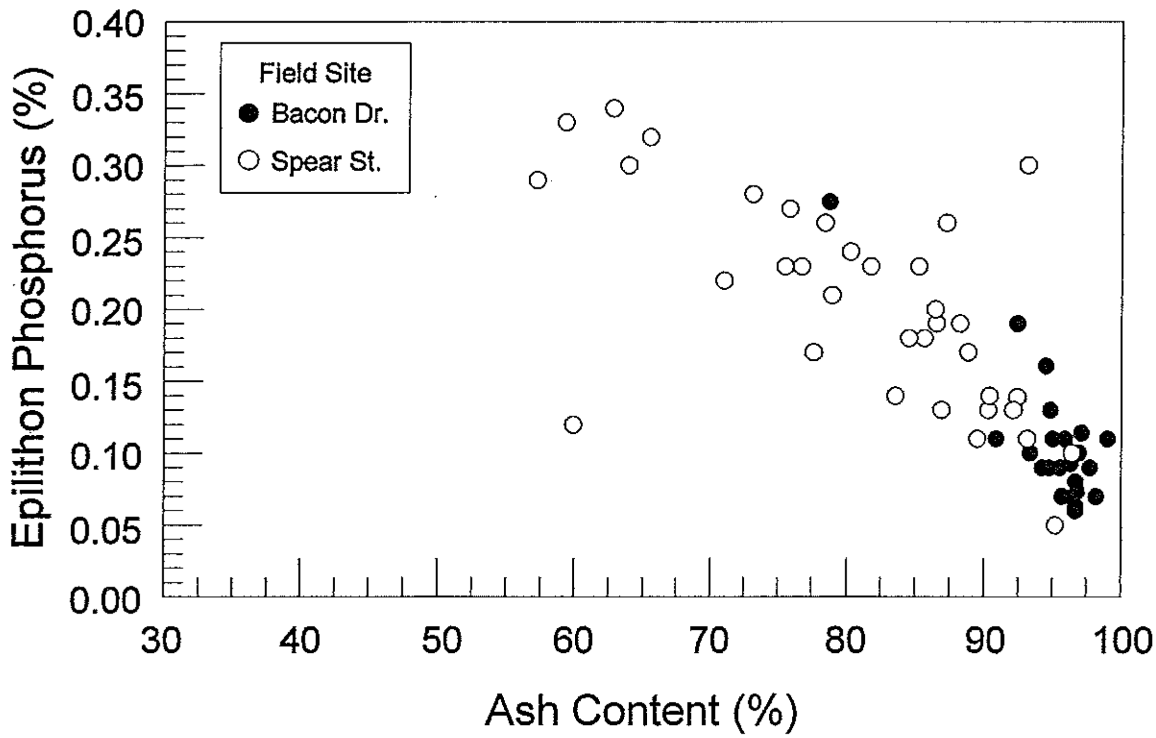


Figure 3.14 Relationship between epilithon phosphorus concentration and % ash for those samples from all seasons that were ashed and analyzed for phosphorus content.

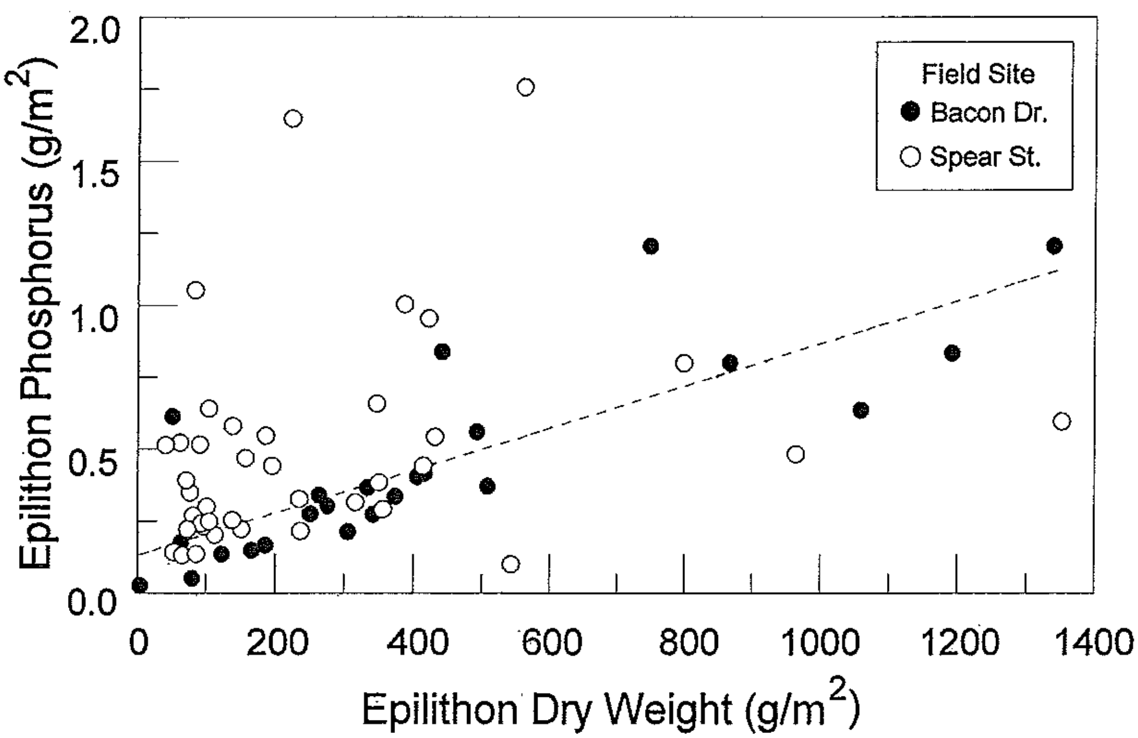


Figure 3.15 Relationship between epilithon P stock and dry weight, both normalized to a unit area of rock surface, for those samples from all seasons that were analyzed for phosphorus. The dashed line represents a significant regression of the data from Bacon Dr. (n=24, R2=0.64). There was no significant relationship for the data from Spear St. (n=39).

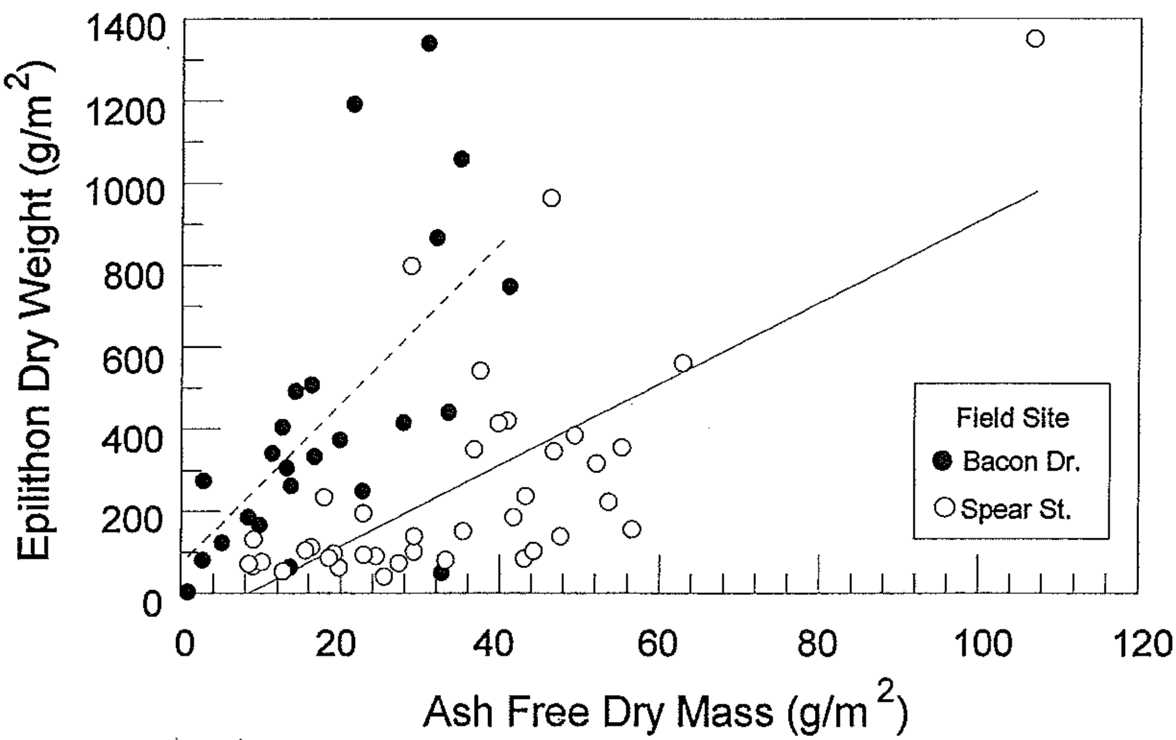


Figure 3.16 Relationship between epilithon dry weight and ash-free dry mass, both normalized to a unit area of rock surface, for those samples that were ashed. The dashed and solid lines represent significant regression fits to the data for Bacon Dr. (n=24, R2=0.35) and at Spear St. (n=39, R2=0.47), respectively. Slopes were significantly different at p=0.1 but not at p=0.05 due to scatter.

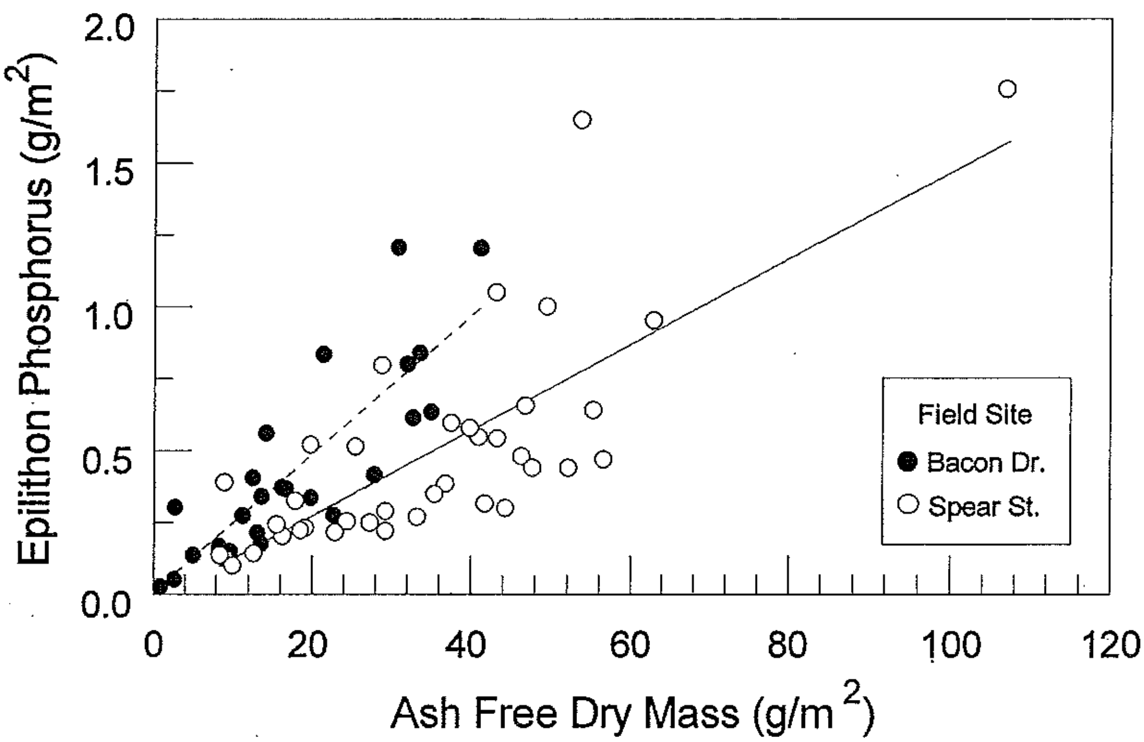


Figure 3.17 Relationship between epilithon P stock and ash-free dry mass, both normalized to a unit area of rock surface, for those samples that were ashed. The dashed and solid lines represent significant regression fits to the data for Bacon Dr. (n=24, R2=0.69) and at Spear St. (n=38, R2=0.24), respectively. Slopes were significantly different at p=0.05.

Table 3.9 Mass, P content, and P store in macrophytes at the two study sites. All masses are dry weights. P stock was estimated as the product of mean plant mass and mean P content. PR identifies the post-rain sampling.

SEASON	NUMBER OF QUADRATS	MACROPHYTE MASS MEAN g/m²	MACROPHYTE MASS SE g/m2	P CONTENT MEAN mg/g	P CONTENT SE mg/g	P STOCK MEAN mg/m²	P STOCK SE mg/m²
Bacon Drive							
SUMMER 93	29	270.0	38.2	4.65	0.19	1255	185
FALL 93*	26	31.1	6.0	16.14	4.33	502	166
WINTER 94	8	0.1	0.1	2.99	0.00	0.2	0.0
SPRING 94	25	1.7	0.4	4.81	0.42	8.3	15.6
SUMMER 94	39	170.3	16.5	3.11	0.08	530	53
SUMMER 94 PR	24	111.5	20.1	2.50	0.13	279	53
SUMMER 94 END**	30	86.1	15.2	NS	NS	NS	48
FALL 94*	40	49.6	10.5	2.88	0.16	143	31
WINTER 95	20	0.0	0.0	NS	NS	0.0	0.0
SPRING 95	40	0.0	0.0	NS	NS	0.0	0.0
Spear Street							
FALL 93*	20	0.55	0.37	4.12	1.63	2.3	1.8
WINTER 94	8	0.00	0.00	0.00	0.00	0.0	0.0
SPRING 94	25	0.26	0.18	10.30	0.14	2.7	1.9
SUMMER 94	40	0.71	0.51	3.49	0.08	2.5	1.8
SUMMER 94 PR	25	3.16	2.95	2.79	0.37	8.8	8.3
FALL 94*	40	2.84	1.15	3.06	0.06	8.7	3.5
WINTER 95	20	0.07	0.07	NS	NS	0.0	0.0
SPRING 95	40	0.00	0.00	NS	NS	0.0	0.0

* An extra sample was taken in late September to better distinguish tends in biomass. P stock was estimated using the P content of August plants.

** Fall samples included moribund and dead macrophyte material (about 75% in Fall 1994).

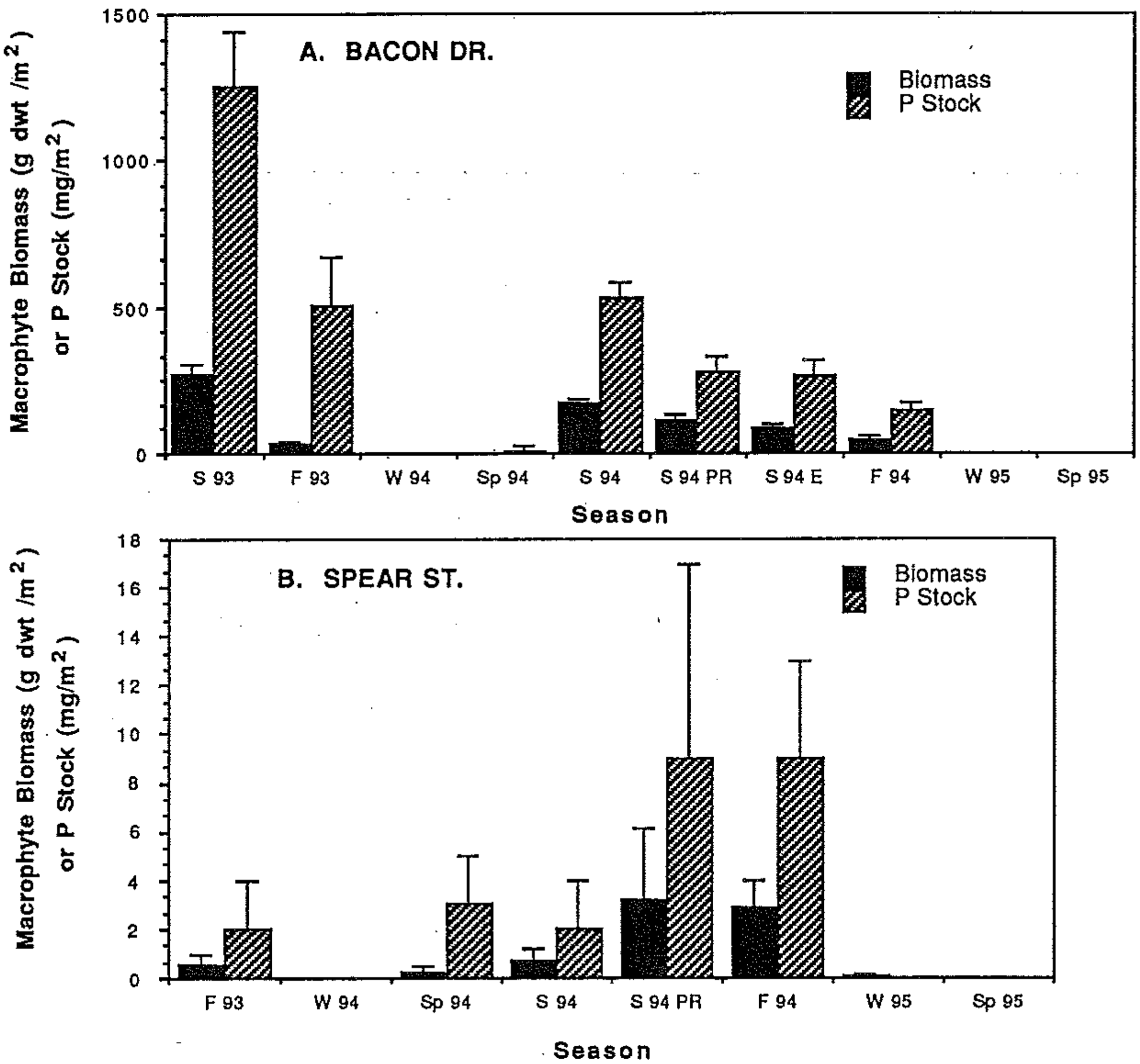


Figure 3.18 Biomass and P stock of macrophytes in the Bacon Dr. (A) and Spear St. (B) reaches at the seasonal samplings. Notice differences in scale.

Table 3.10 Mass, P content, and P store in epiphytes at the two study sites.All masses are dry weights. Biomass per m^2 of reach was estimated as the product of specific biomass (g epiphyte/g macrophyte) and macrophyte mass. This value times mean P content yielded an estimate of P storage. Epiphyte sampling was done only at Bacon Dr. P storage in epiphytes for Spear St. was estimated using specific biomass and P content values for Bacon Dr. on the same date. To calculate stocks for dates when epiphytes were not sampled, experimental averages for P content and specific biomass were used.

SEASON	SPECIFIC MASS g/g macrophyte		BIOMASS IN REACH g/m²		P CONTENT mg/g		P STOCK mg/m²	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
Bacon Drive								
SUMMER 93	0.325	0.064	94.3	22.9	2.02	0.35	190.4	56.6
FALL 93	0.095	0.025	2.95	0.97	NS	NS	6.74	2.74
WINTER 94	NS	NS	0.05	0.04	NS	NS	0.12	0.09
SPRING 94	NS	NS	1.15	0.40	NS	NS	2.62	1.11
SUMMER 94	0.773	0.288	131.6	50.7	3.14	0.55	413.2	1.5
SUMMER 94 PR	1.473	0.292	164.1	44.0	1.69	0.76	276.9	145.1
FALL 94	NS	NS	33.0	10.9	NS	NS	75.4	30.8
WINTER 95	NS	NS	0.00	0.00	NS	NS	0.00	0.00
SPRING 95	NS	NS	0.00	0.00	NS	NS	0.00	0.00
Spear Street								
FALL 93	NS	NS	0.05	0.04	NS	NS	0.11	0.08
WINTER 94	NS	NS	0.00	0.00	NS	NS	0.00	0.00
SPRING 94	NS	NS	0.17	0.13	NS	NS	0.40	0.34
SUMMER 94	NS	NS	0.55	0.44	NS	NS	1.72	0.00
FALL 94	NS	NS	1.89	0.89	NS	NS	4.3	2.3
WINTER 95	NS	NS	0.05	0.05	NS	NS	0.00	0.00
SPRING 95	NS	NS	0.00	0.00	NS	NS	0.00	0.00

spring sampling of 1994, showed plants present within both reaches, while the April sampling of 1995 did not. Biomass peaked at the Bacon Dr. reach in summer, with mean estimates of 270 ($\pm$ 38) g DW/m^2 and 170 ($\pm$ 17) g DW/m^2 obtained in 1993 and 1994, respectively. In 1994, three summer samplings were done at Bacon Dr. These showed that macrophyte biomass declined steady between early August and October, apparently because sloughing began to overcome plant growth during this period. At the Spear St. site, macrophyte biomass was as high or higher in autumn than in summer, possibly because flow rates were lowest at this time (section 2.1) and biomass accumulation in riffle reaches is often limited by superoptimal water flow. The maximum biomass measured, however, was just 3.1 ($\pm$ 3.0) g DW/m^2. Plant tissue concentrations of P did not vary significantly with season (although there were some outliers; Table 3.9). Hence, seasonal trends in P storage were similar to those in biomass storage (Table 3.9). Epiphyte data were collected only in summer and fall, and thus could not be analyzed for seasonal trends. The winter and fall P stock values included in Table 3.10 assume similar epiphyte coverage on plants throughout the year and calculate stock on the basis of macrophyte abundance. Epiphyte biomass was greatest on *Elodea*, followed by sago pondweed, then floating leaf pondweed (Figure 3.19).

3.1.5 Detritus

The mass of detritus present on the bottom (CPOM - coarse particulate organic matter) varied considerably between sampling times (Table 3.11). At both sites, more CPOM was present in autumn than at other times of year, principally because of the leaf litter blown or washed into the stream during this time.

At the Spear St. site, the lowest CPOM levels were detected in winter, with intermediate levels present in spring and summer. At the Bacon Dr. reach, summer detritus levels were

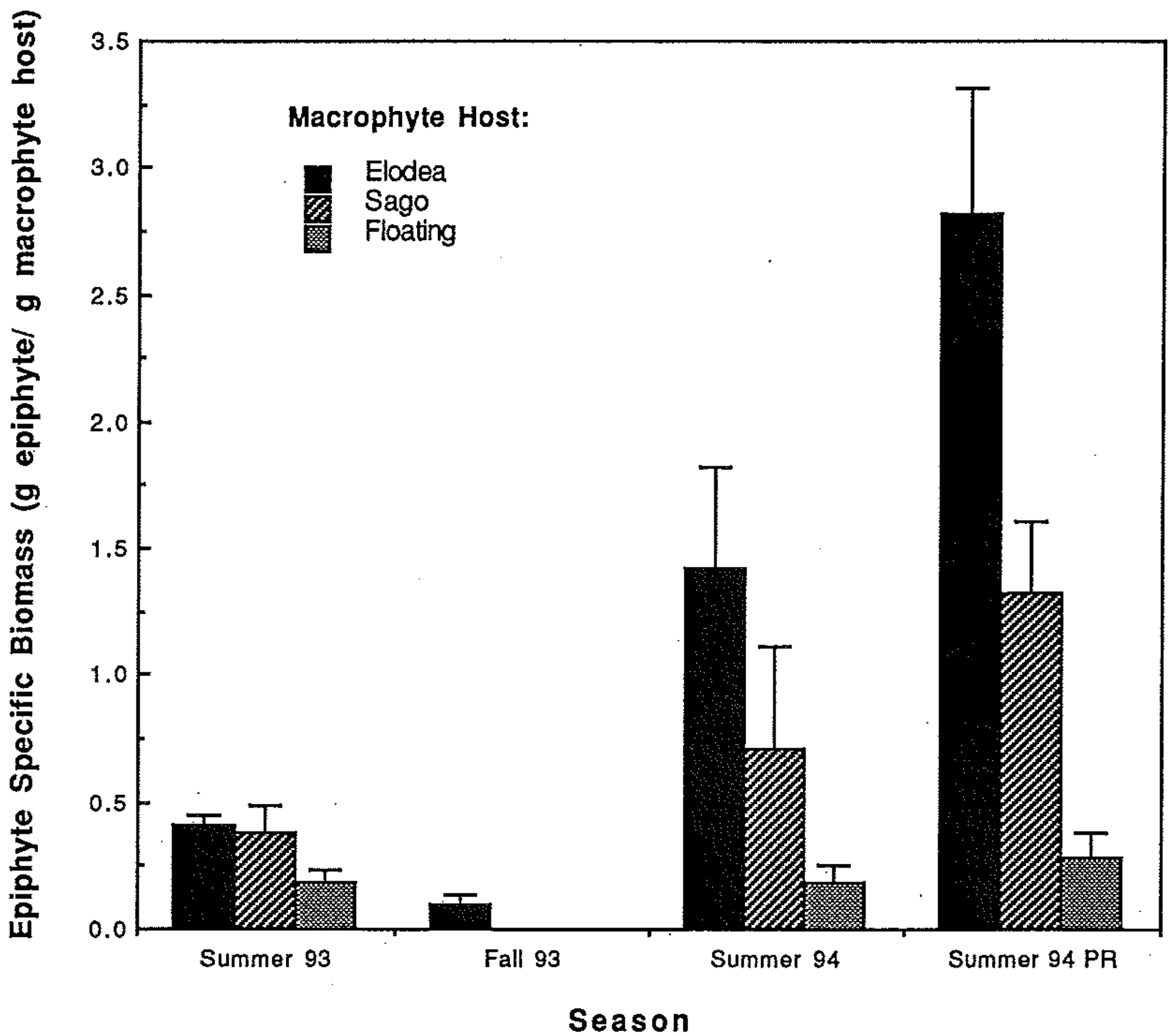


Figure 3.19 Biomass of epiphytes present on different macrophytes at different seasons at Bacon Dr. Only *Elodea* was sampled in Fall 1993.

Table 3.11 Phosphorus storage in benthic CPOM (detritus > 1 cm in length, but excluding wood larger than twigs >1 cm diameter) at the two study sites All masses are dry weights. P stock content. PR identified was estimated as the product of mean detrital mass and mean P the post-rain sampling.

SEASON	DETRITAL MASS		P CONTENT		P STOCK	
	MEAN g/m^2	SE g/m^2	MEAN mg/g	SE mg/g	MEAN mg/m^2	SE mg/m^2
Bacon Drive						
SUMMER 93	7.56	3.11	0.98	0.23	7.43	3.51
FALL 93*	174.96	38.58	2.43	0.77	424.45	163.32
WINTER 94	6.08	5.54	4.54	3.22	27.62	31.86
SPRING 94	22.90	9.31	1.62	0.18	37.00	15.62
SUMMER 94	3.48	1.83	1.45	0.22	5.03	2.75
SUMMER 94 PR	5.42	1.29	1.16	0.15	6.30	1.70
FALL 94*	32.92	7.21	1.54	0.11	50.63	11.71
WINTER 95	44.53	19.03	1.05	0.11	46.80	20.60
SPRING 95	23.34	6.81	0.79	0.08	18.39	6.00
Spear Street						
FALL 93*	12.51	7.82	4.23	1.63	52.89	38.84
WINTER 94	0.75	0.75	1.65	0.00	1.24	1.24
SPRING 94	6.81	3.53	0.99	0.14	6.74	3.62
SUMMER 94	7.29	1.80	0.80	0.08	5.85	1.57
SUMMER 94 PR	2.37	0.72	1.57	0.37	3.71	1.42
FALL 94*	32.74	8.61	1.44	0.06	47.08	12.52
WINTER 95	2.42	1.75	0.89	0.15	2.15	1.00
SPRING 95	9.28	3.94	1.06	0.26	9.84	5.00

* Dead leaves and stems still attached to live macrophytes were not collected as detritus, but as macrophyte samples. In fall, macrophytes were dying back so that as much as 75% of their mass was yellow or dead. The fall estimates of detritus are therefore underestimates.

lower than spring levels; detritus levels for the two winters differed greatly (one was high, one low). The phosphorus content of the detritus also varied somewhat between samplings, probably because of variability in the relative importance of leaves, macrophytes and twigs in samples.

As a result of variance in both detrital mass and detrital P content, the standing stock of P in CPOM varied over two orders of magnitude during the study period. At both study sites, P storage was greatest in autumn. At the Bacon Dr. site, P storage in CPOM was lowest in summer, whereas, at Spear St., winter, spring and summer values were similar. Analysis of variance indicated that CPOM storage was significantly greater ($p < 0.05$) at Bacon Dr. than at Spear St. CPOM in suspension (Table 3.12) was a small portion of the total CPOM in the stream reach, and also a small pool relative to TP. Even in fall, the flux of detrital P moving downstream was <1% of the total P flux (compare with Table 3.2). A significant relationship between CPOM in suspension and flow velocity was found (Figure 3.20).

The mass of wood in the stream reaches (Table 3.13) was generally high relative to the mass of CPOM, while its P content was lower. Wood was clearly an important P stock: estimates of mean wood mass ranged from 0.02-1.79 g/m^2, while the CPOM means ranged from 0.001-0.424 g/m^2. Wood decomposes and releases P very slowly, however. Most likely, the P in wood is transported downstream without substantial interaction with other compartments.

3.1.6 Summary of Phosphorus Stocks

Total P stock estimates for each seasonal stock assessment at each site are summarized in Table 3.14 and in Figures 3.21 and 3.22. Note that TP stock data for Bacon Dr. for all compartments except sediment are replotted at a different scale in Figure 3.23 in order to

Table 3.12 Standing stock and daily downstream flux of suspended CPOM and suspended CPOM P at the two study sites. P stock was calculated as the product of suspended CPOM mass and the mean P content of material collected on traps throughout the study, 4.490 (± 1.842) and 2.695 (± 0.842) mg/g for Bacon Dr. and Spear St. respectively. The discharge data used to calculate fluxes are shown in Table 3.2. PR identifies the post-rain event.at the two study sites.

SEASON	SUSPENDED CPOM MASS mg/m³	P STOCK mg/m²	SUSPENDED CPOM FLUX kg/day	P FLUX g/day
Bacon Drive				
SUMMER 93	0.3	0.001	NS	NS
FALL 93	73.2	0.126	3.76	16.9
WINTER 94	NS*	NS	NS	NS
SPRING 94	NS	NS	NS	NS
SUMMER 94	2.6	0.004	0.058	0.26
SUMMER 94 PR	3.5	0.006	0.087	0.39
FALL 94	10.1	0.011	0.136	0.61
WINTER 95	NS	NS	NS	NS
SPRING 95	4.0	0.006	0.167	0.75
Spear Street				
FALL 93	4.5	0.004	0.152	0.41
WINTER 94	NS	NS	NS	NS
SPRING 94	NS	NS	NS	NS
SUMMER 94	16.7	0.011	0.245	0.66
SUMMER 94 PR	3.9	0.002	0.071	0.19
FALL 94	35.6	0.014	0.349	0.94
WINTER 95	NS	NS	NS	NS
SPRING 95	2.3	0.002	0.059	0.16

* No samples were collected in winter due to ice cover or in Spring 1994 due to flows too high to keep the trap in place.

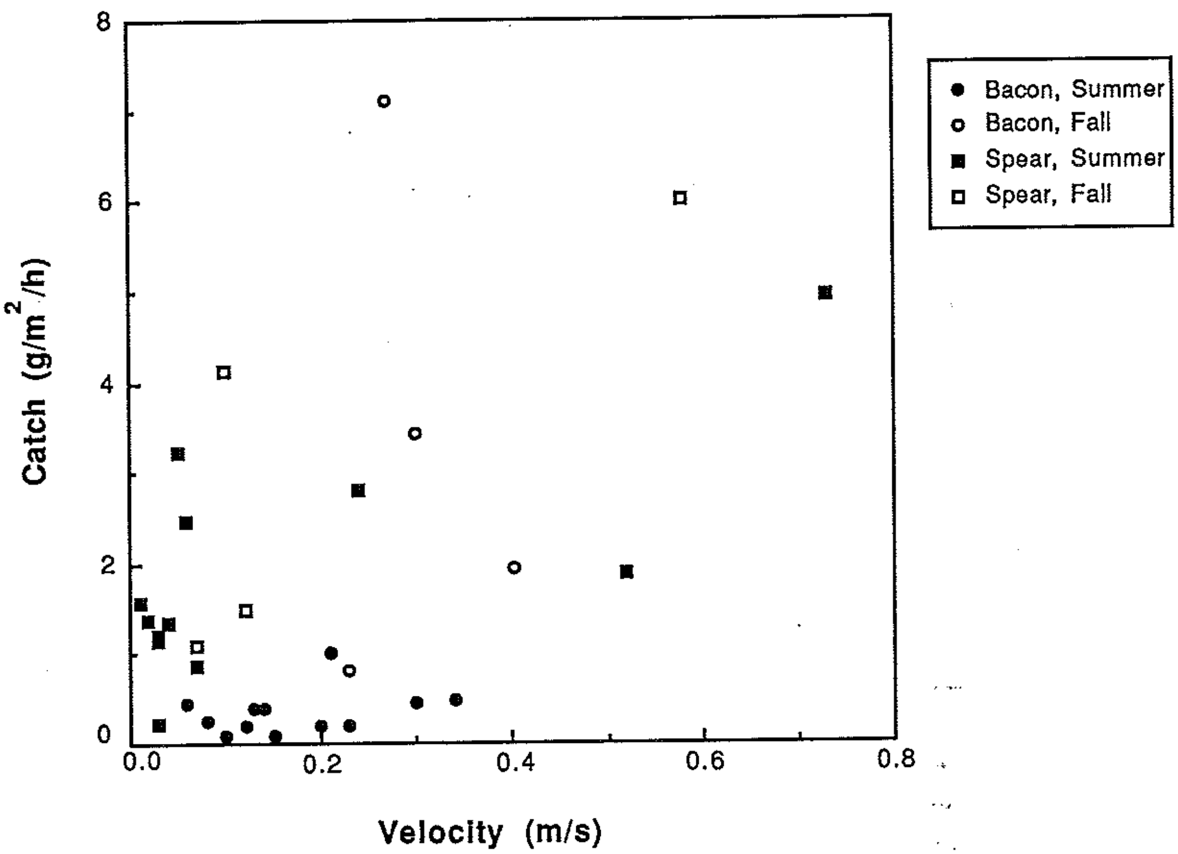


Figure 3.20 Relationship between trap catch and flow velocity. r=0.491, n=34, p=0.05. Two samples collected at maximum leaf fall are excluded.

Table 3.13 Phosphorus storage in wood at the two study sites. P stock was calculated as the product of wood mass and the mean P content of wood samples collected from both sites over the course of the study, 0.974 (± 0.443) mg/g.

SEASON	WOOD MASS		P STOCK	
	MEAN g/m^2	SE g/m^2	MEAN mg/m^2	SE mg/m^2
Bacon Drive				
SUMMER 93	108.37	74.79	106	73
FALL 93	43.95	19.34	43	19
WINTER 94	NS*	NS	NS	NS
SPRING 94	605.79	453.61	590	442
SUMMER 94	505.64	142.29	492	625
SUMMER 94 PR	35.47	28.15	35	28
FALL 94	121.90	56.64	119	57
WINTER 95	NS	NS	NS	NS
SPRING 95	133.20	86.51	130	84
Spear Street				
FALL 93	12.74	6.88	12	39
WINTER 94	NS	NS	NS	NS
SPRING 94	154.39	67.93	150	93
SUMMER 94	1839.60	1778.70	1792	2451
SUMMER 94 PR	30.32	27.80	30	28
FALL 94	20.54	5.50	20	14
WINTER 95		NS	NS	NS
SPRING 95	42.68	23.23	42	23

*No samples were collected in winter due to ice cover show the variations suppressed at the scale of total reach stocks shown in Figure 3.22. The P storage patterns in the two reaches differed markedly. The Bacon Dr. reach stored more than ten times the amount of P stored in as the Spear St. reach, an average of 33.3 g/m^2 compared to just 2.8 g/m^2 in the Spear St. reach. While the majority of TP was stored in sediments in both reaches, nearly all (97%) of the TP was stored in sediments at Bacon Dr. compared to the 80% sediment P at Spear St. It is important to note that we considered the top 5 cm of sediment as the "active" stock. Macrophytes and epiphytes stored a negligible amount of P at Spear St. where plants were scarce; macrophytes and epiphytes stored as much as 3% of reach TP at Bacon Dr. when plants were abundant. A very small proportion of P was stored in detritus, except on one stock assessment at Spear St., when a large log happened to be sampled. Less than 1% of total reach P was ever contained in the water compartment.

The two reaches also differed in the seasonal variation of P stocks. Total P stocks at Bacon Dr. were remarkably consistent over the study period, with little apparent seasonal variation. Total P stocks at Spear St., however, peaked in summer and fall and reached minima during the winter. There was also some seasonal variation in the distribution of P stocks among compartments at Spear St., while except for a small jump in macrophyte P in summer, distribution of P among compartments at Bacon Dr. was consistent throughout the study period. Although only a small component of total P stocks, macrophyte P stock at Bacon Dr. peaked during summer and fall (Figure 3.23). Not surprisingly, detritus P was highest in the fall. Epilithon P stocks were lowest in winter, but otherwise relatively constant at Bacon Dr.

3.1.7 Effects of 1994 Summer Storm

The 1994 summer storm increased discharge from 0.03 m^3/sec (1.0 ft^3/sec) on August 2 to

Table 3.14 Summary of total phosphorus (TP) stocks in stream compartments for each stock assessment. Totals represent total in-stream TP stock at each stock assessment. Means indicate TP stock for each compartment averaged over all stock assessments, with the average percent of total in-stream stock occurring in that compartment.

SPEAR ST.	Water	(se)	Sediment	(se)	Epilithon	(se)	Macrophytes*	(se)	Detritus	(se)	TOTAL
SEASON	(mg/m2)										
S, 93	--				680	(280)					680
F, 93	20	(<1)	2536	(364)	1120	(140)	2	(2)	65	(78)	3743
W, 94	16	(<1)	1596	(247)	260	(60)	0	(0)	163	(72)	2035
Sp, 94	14	(<1)	2510	(574)	600	(290)	3	(2)	157	(97)	3284
S, 94	34	(<1)	1612	(208)	560	(260)	4	(2)	1798	(2453)	4008
F, 94	12	(<1)	2895	(443)	430	(110)	19	(9)	67	(27)	3423
W, 95	11	(<1)	1963	(390)	430	(40)	0	(0)	33	(33)	2437
Sp, 95	8	(0)	2421	(296)	120	(10)	0	(0)	52	(28)	2601
		%		%		%		%		%	
MEAN	16	0.6	2219	79.9	525	18.9	4	0.1	334	12.0	2776

* Includes epiphytes

BACON DR.	Water	(se)	Sediment	(se)	Epilithon	(se)	Macrophytes*	(se)	Detritus	(se)	TOTAL
SEASON	(mg/m2)										
S, 93	--		22964	(2413)	370	(120)	1446	(242)	113	(77)	24893
F, 93	23	(<1)	26478	(1832)	190	(190)	509	(169)	467	(182)	27667
W, 94	22	(5)	36164	(7056)	0	(0)	0	(0)	344	(26)	36530
Sp, 94	22	(<1)	37151	(2380)	240	(100)	11	(17)	627	(458)	38051
S, 94	42	(1)	30330	(2548)	220	(80)	943	(228)	497	(628)	32032
F, 94	15	(1)	38257	(5784)	240	(80)	323	(94)	170	(69)	39005
W, 95	12	(<1)	36380	(3802)	70	(10)	0	(0)	171	(91)	36633
Sp, 95	7	(1)	31425	(2290)	100	(10)	0	(0)	148	(90)	31680
		%		%		%		%		%	
MEAN	20	0.1	32394	97.2	179	0.5	404	1.2	317	1.0	33311

* Includes epiphytes

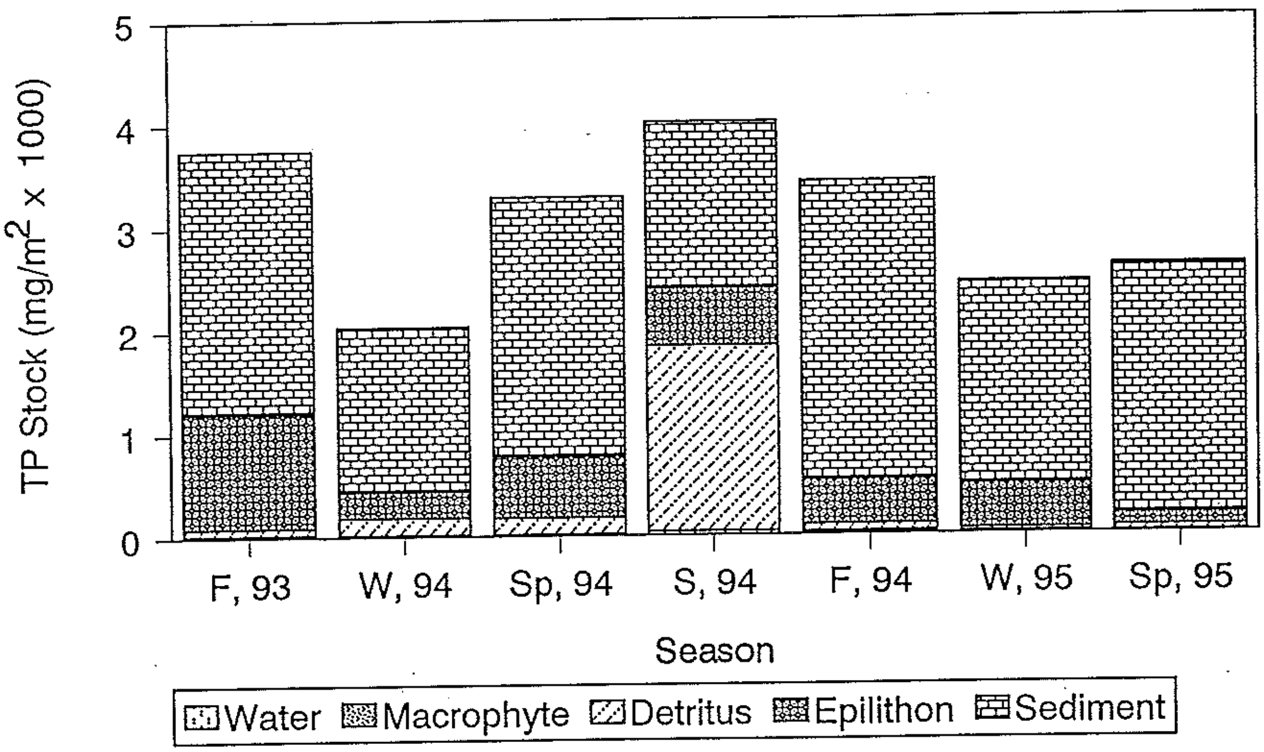


Figure 3.21 Distribution of total phosphorus (TP) stocks among all stream compartments at seasonal stock assessments, Spear St. reach.

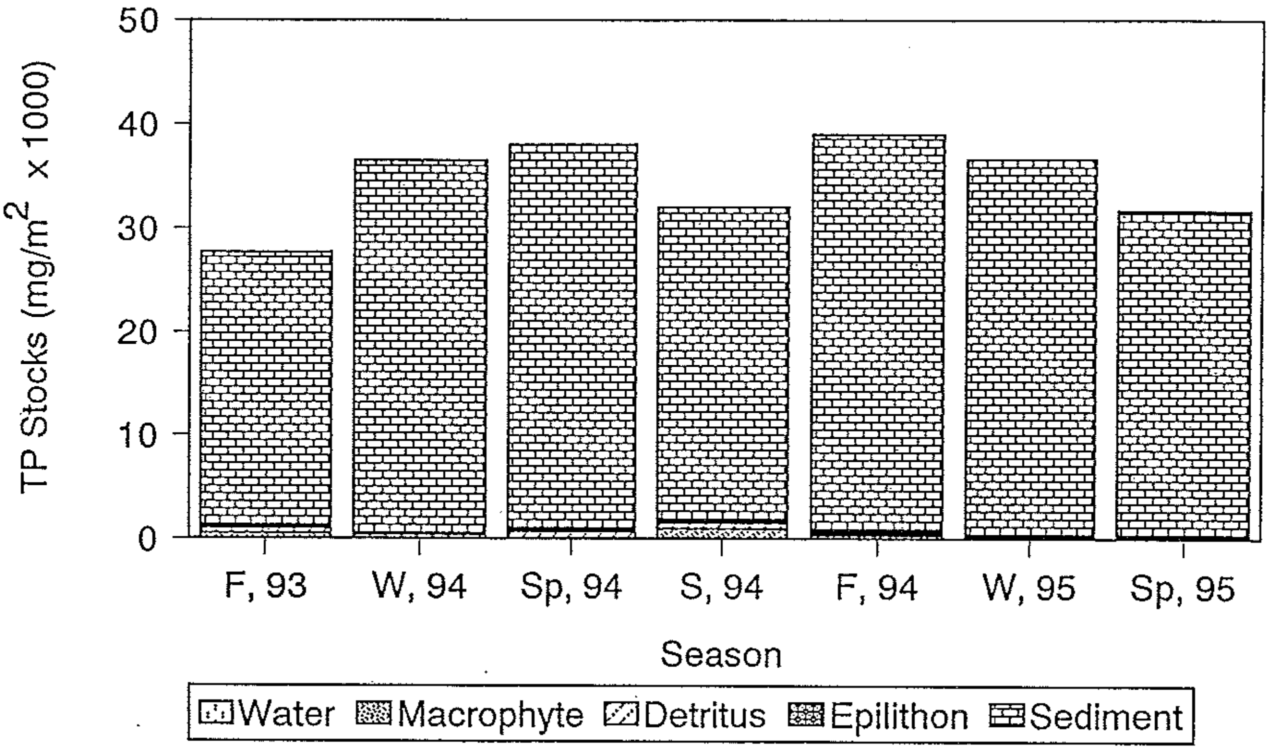


Figure 3.22 Distribution of total phosphorus (TP) stocks among all stream compartments at seasonal stock assessments, Bacon Dr. reach.

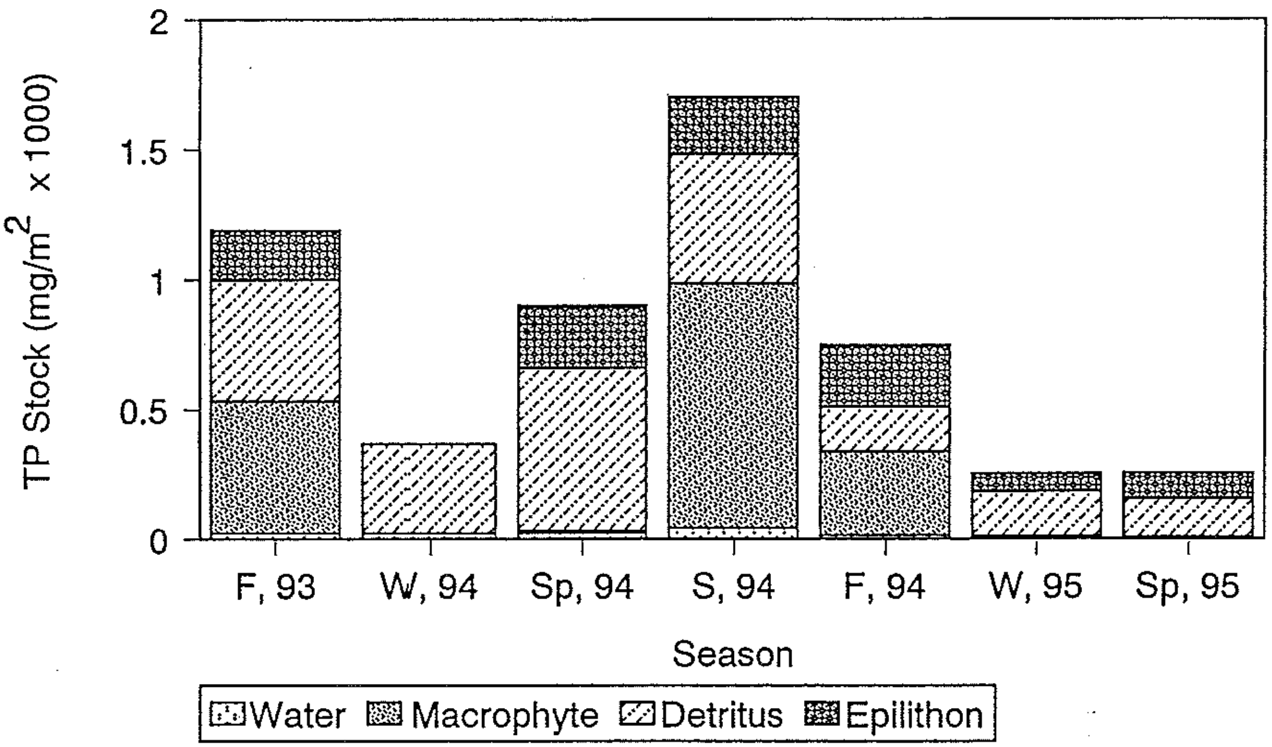


Figure 3.23 Distribution of total phosphorus (TP) stocks among all stream compartments (except sediment) at seasonal assessments, Bacon Dr. reach

a peak of 0.26 m^3/sec (9.2 ft^3/sec)on August 7. The storm effects on sediments at both Spear St. and Bacon Dr. were assessed by analyzing samples collected at transect stations before and after the August 1994 storm. The results are shown in Table 3.15 and Figures 3.24 and 3.25. At Spear St. the proportions of both sand and silt+clay were lower in all samples after the storm suggesting erosion and downstream transport of these size fractions. At Bacon Dr., average values for two out of the three depth intervals exhibited a decrease in the percent of silt+clay. The difference was most striking in the 0-1 cm layer. This layer initially had approximately 19 wt.% silt+clay suggesting surface deposition, but after the storm had only 5 wt.% silt+clay, similar to the deeper sediment horizons. There were no discernible patterns of enrichment or depletion in TP at either site. Movement of the four rings on the scour chain posts indicated erosion at three of the locations and subsequent deposition at one site. The average *net* erosion (erosion minus deposition) was 2.5 cm.

A comparison of the before and after epilithon dry weight shows over a 100% increase over a seven-day period, and corresponding increases in AFDM and P stock (Table 3.16). A two-tailed t-test showed this to be a significant increase in dry weight ($p < 0.025$) and implies an average accumulation rate over this period of 16 g/m^2/d.

High flow events can uproot plants, or alternatively stimulate plant growth by removing epiphytes. Sampling of macrophytes at Bacon Dr. before and after the storm event, showed a 35% decline in plant biomass (Table 3.9). At Spear St., no removal of plant mass was apparent. Higher epiphyte biomass per unit mass of macrophyte was measured at the Bacon Dr. site after the storm event than before (Table 3.10, Figure 3.19). The impact was most apparent for epiphytes on *Elodea*: 1.4 grams of epiphyte/gm of plant were present before the rain, and 2.8 gm per gm afterwards. The increased biomass may have been the result of silt and clay trapping. During the storm event, the water became quite

Table 3.15 Sediment size and composition pre- and post-storm at Spear St. and Bacon Dr. Mass per unit area at Spear St. assumes 28% of the surface is interstitial material; mass per unit area at Bacon Dr. is for the interval indicated.

Spear St.						
Sample	Wt.% Gravel	Wt.% Sand	Wt.% Silt+Clay	mg TP/gm sand	mg TP/gm silt+clay	mg TP/m^2
T1- Pre	58.5	40.2	1.3	0.37	1.40	5657
T1-Post	75.6	24.1	0.3	0.28	1.76	1887
T2- Pre	68.3	31.7	2.1	0.28	1.59	3254
T2-Post	70.9	28.0	1.1	0.37	6.54	4763
T3-Pre	76.4	23.0	0.6	0.60	1.68	4142
T3-Post	85.3	14.3	0.3	0.22	1.50	1125
Bacon Dr (averages of three transect sites)						
Sample	Wt.% Gravel	Wt.% Sand	Wt.% Silt+Clay	mg TP/gm sand	mg TP/gm Silt+Clay	mg TP/m^2
0-1cm Pre	17.7	63.1	19.3	0.28	1.12	16180
0-1cm Post	18.7	75.8	5.4	0.40	1.18	22487
1-2cm Pre	23.9	74.1	2.0	0.44	1.05	14916
1-2cm Post	19.5	76.0	4.5	0.30	1.02	13285
2-5cm Pre	26.9	66.8	6.3	0.33	1.00	39993
2-5cm Post	13.3	84.4	2.4	0.32	1.13	43543

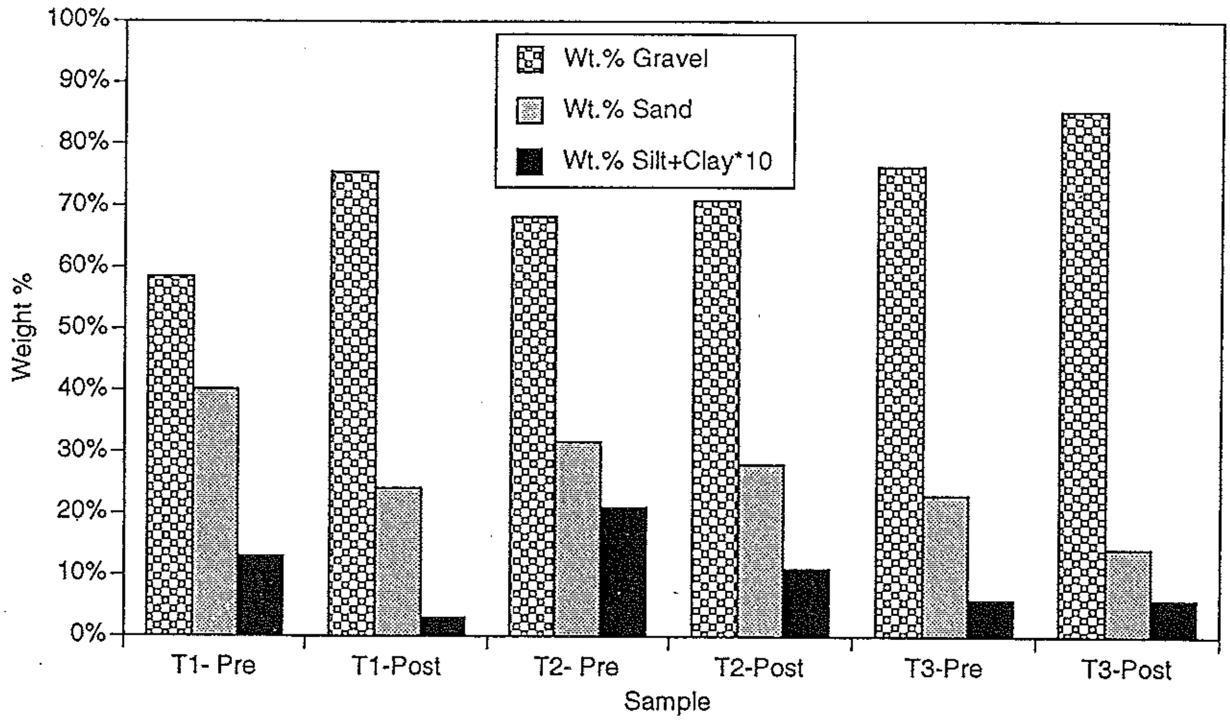


Figure 3.24 Pre- and post-storm grain size wt.%; Spear St. (Note 10x scale expansion for "silt+clay")

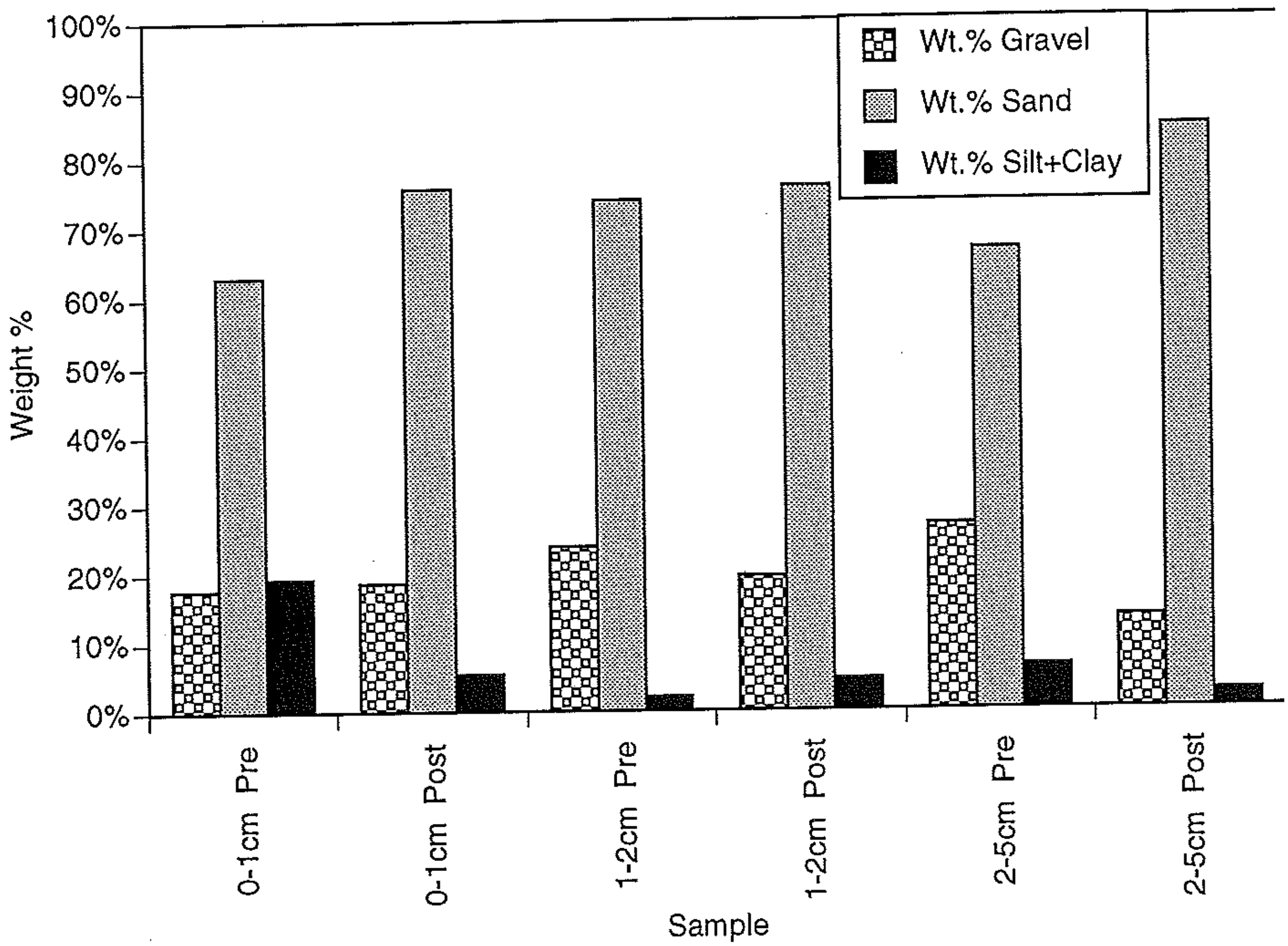


Figure 3.25 Pre- and post-storm grain size wt.%; Bacon Dr.

Table 3.16 Mean periphyton dry weight (± 1 SE, n=19) and calculated ash-free dry mass and P (± 1 SE) for Spear St. site sampled on 8/01/94 and 8/08/94, before and after a storm event. Values are in g/m^2.

	Before	After
Dry Weight	106.9 (± 17.6)	219.5 (± 43.7)
AFDM	23.7 (± 4.6)	48.6 (± 11.0)
Phosphorus	0.20 (± 0.04)	0.40 (± 0.10)

turbid. Furthermore, the phosphorus concentration of epiphytes after the storm event was lower than before the storm event (Table 3.10).

Detrital CPOM storage in the two stream reaches did not change significantly as a result of the storm event. The data in Table 3.13 suggesting massive wood transport out of the stream reaches during the storm event are suspect. During the pre-event sampling, wood was thrown out of transects after it was measured (to ensure that it wouldn't be remeasured). Post-storm transects were set up without considering the cleared areas. If pre- and post-storm transects overlapped, the latter would be found to be largely clear of wood.

Comparison of water P stocks before and after the event is not meaningful, as a completely different water mass was moving through the reaches and there was no knowledge of other factors influencing water P concentrations outside the reaches, e.g. dilution of point source discharge or addition of runoff-borne P to the stream.

3.2 P SPECIATION IN THE LAPLATTE

Total (TP), total dissolved (TDP), soluble reactive (SRP), and bioavailable (BAP) were measured in the water at each seasonal sampling. NaOH-P, HCl-P, and Organic-P associated with the in-stream sediments were also measured at each seasonal sampling.

3.2.1 TP, TDP, and SRP in the Water

SRP and TP concentrations in water were nearly identical between and within the study reaches on any given sample date and were highest during the summer of 1994 and lowest during the spring of 1995 (Figure 3.26). The percentage of TP that was SRP varied seasonally with lowest values in the winter and spring (about 40%) and highest values in the summer and fall (about 80%). Over the course of the study, concentrations ranged

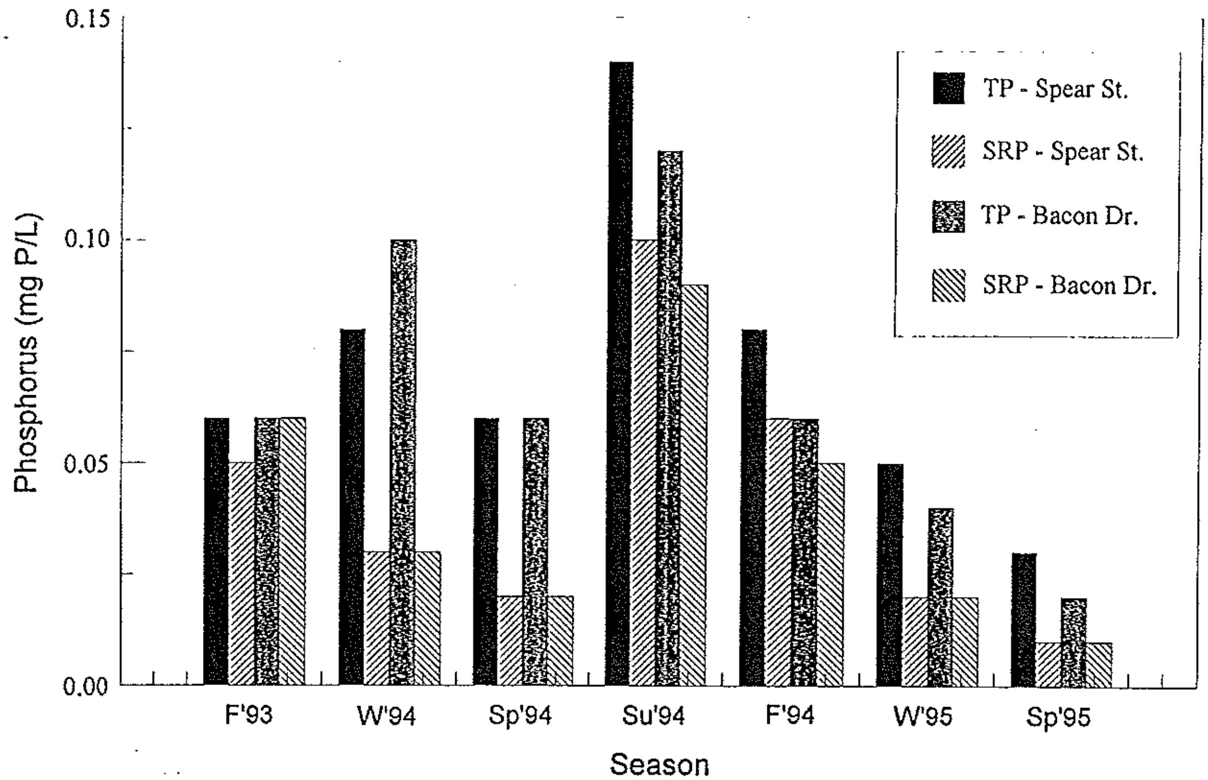


Figure 3.26 Seasonal variation in total and soluble reactive phosphorus concentrations at the Bacon Dr. and Spear St. sites

from 0.01 - 0.10 mg P/l for SRP and from 0.02 - 0.19 mg P/l for TP. Concentrations were markedly lower than values reported prior to the upgrading of the Hinesburg sewage treatment plant, only about 20 % of levels reported from 1980s - 1989 (Meals 1990). Samples during Spring 1995 (April 11, June 12 and 13) were also analyzed for TDP, as well as SRP and TP. SRP concentrations for those dates averaged about 40 % of TP (range: 33 to 50 %), whereas TDP concentrations averaged about 65 % of TP(range: 50 to 84 %).

3.2.2 Bioavailable P in the Water

BAP was highest during the summer of 1994 following the modest storm and lowest during Fall 1994 and Spring 1995, and higher on all three sampling dates at Bacon Dr. than at Spear St. (Figure 3.27). On average almost twice as much BAP was measured at Bacon Dr. as at Spear St. The percentage of TP that was BAP varied seasonally with lowest values in the fall (4 and 12 % at Spear St. and Bacon Dr., respectively) and highest values in the summer (19 and 35 % at Spear St. and Bacon Dr., respectively). The percentage of SRP that was BAP varied seasonally with lowest values also in the fall (5 and 14 % at Spear St. and Bacon Dr., respectively), whereas highest values occurred in the spring (75 and 100 % at Spear St. and Bacon Dr., respectively).

3.2.3 Extractable P in Sediment

As previously discussed (Section 2.2.1.2.) separate sediment samples were analyzed for NaOH extractable-P and HCl extractable-P. Thus, analytically measured HCl-P includes NaOH-P. The reported values for HCl-P are the analytically measured values minus NaOH extractable-P (mg P/g dry sediment). NaOH extractable-P is often considered indicative of "biologically available P" (Böstrom et al. 1988, Hosomi et al. 1981, Young and DePinto 1982) which is released by $(OH)^-$ substitution, whereas HCl-P is considered representative of inorganic, mineralogically-bound P released by acid dissolution. Because

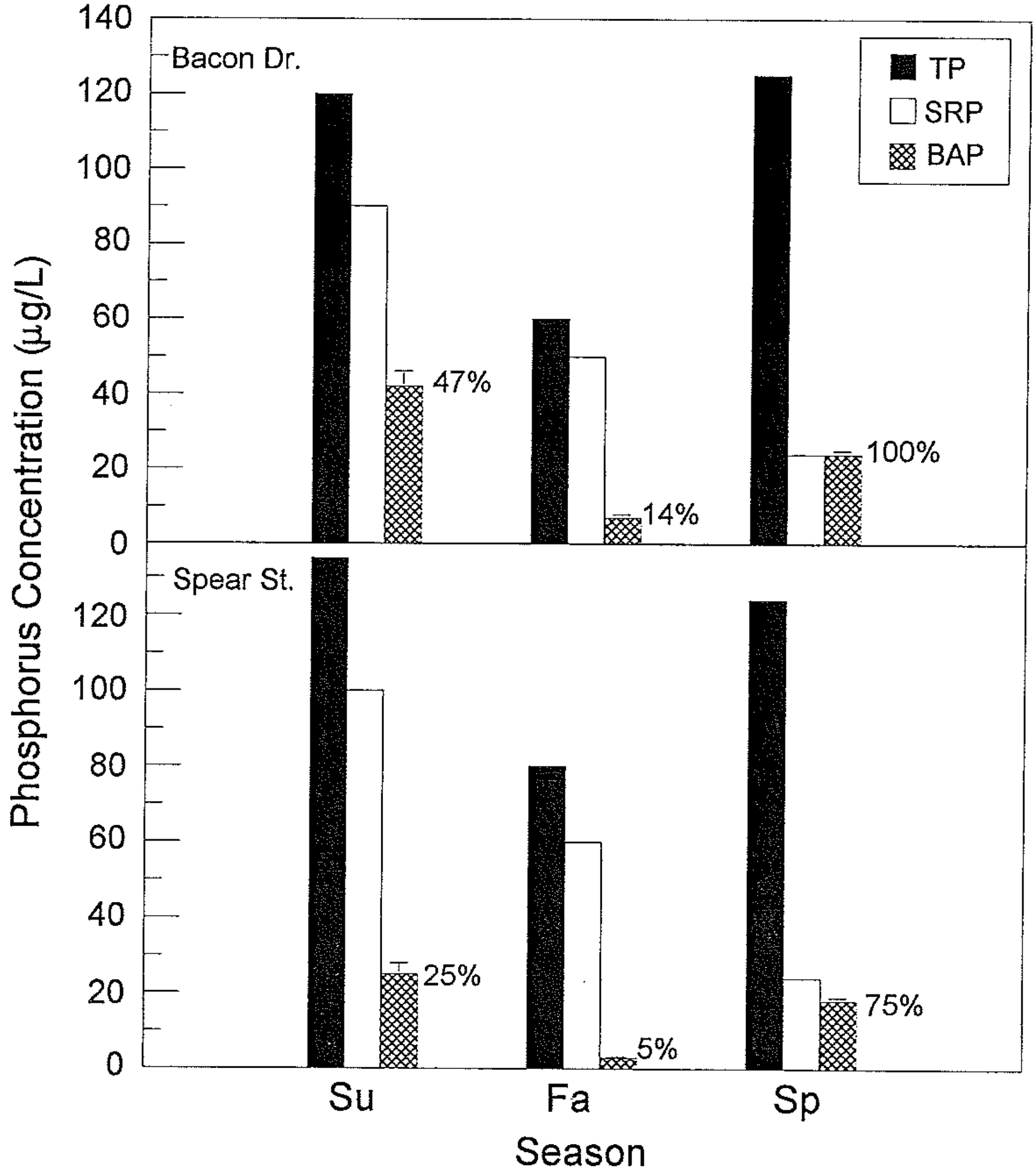


Figure 3.27 Mean concentration of total, soluble reactive and bioavailable phosphorus for Bacon Dr. and Spear St. on the Summer and Fall 1994 and Spring 1995 sample dates (n=2 to 4, 1 SE shown). The indicated percentages refer to the proportion of SRP that is BAP.

separate aliquots of individual sediment samples were extracted, and because individual samples exhibit heterogeneity, summation of extraction components is not possible. For example, the negative values of HCl-P in some Spear St. silt+clay samples are believed to result from the preponderance of NaOH-P in these samples plus variability in the P concentration among individual aliquots of a sample used for analysis. Nevertheless, these analyses provide an indication of P speciation within the LaPlatte River sediments.

Although highly variable, NaOH-P averaged approximately 16% and HCl-P about 68% of the P present in the Spear St. bulk sediment. Although NaOH-P dominated the silt+clay size fraction, HCl-P was the most prevalent form in the sand size sediment. In determining the distribution of P in bulk sediment, it was assumed that the contribution from >2 mm sediment is negligible although epilithic P is undoubtedly present. These averages (n=4) do not include one analysis in which the HCl-P appears erroneously high (4 times higher than other values) . These data are summarized in Tables 3.17. and 3.18.

Sediments from Bacon Dr. were not differentiated on the basis of size. The P concentrations and percentages given in Table 3.18 are for total sediment (5 analyses in which HCl-P measured on one aliquot exceeded TP measured on a different aliquot of the same sediment sample have been omitted from the averages). With the exception of slightly higher organic-P contents, the P distributions in the Bacon Dr. sediments were similar to those at Spear St. with HCl-P dominating at 62%. Organic -P, calculated as TP - (NaOH-P + HCl-P), was a approximately 23% of Total-P and NaOH-P is 14%. There was a suggestion of higher concentrations of all forms of P in the uppermost sediment layer (0 -2 cm) but areal heterogeneity resulting in large standard error made confirmation difficult.

Table 3.17 Phosphorus extractions from Spear St. sediments (all values are averages, n=4)

Size			TP (mg/g)		NaOH-P (mg/g)		HCl-P (mg/g)*	
% Gravel	% Sand	% Silt+Clay	Sand	Silt+Clay	Sand	Silt+Clay	Sand	Silt+Clay
62.9	28.5	0.5	0.364	1.849	0.058	1.056	0.241	0.079
				% of TP				
			%NaOH-P	% HCl-P	% Org. P			
			16	68	16			
			* HCl-P is analytical value minus NaOH-P					

Table 3.18 Phosphorus extractions from Bacon Dr. sediments (HCL-P* = HCL-P - NaOH-P)

	TP	NaOH-P	HCl-P*	Wt.%	Wt.%	Wt.%
	mg/g dry sed	mg/g dry sed	mg/g dry sed	NaOH-P	HCl-P*	Org.P
All levels (n = 36)						
Average	0.534	0.073	0.318	14%	62%	23%
Std.Dev	0.186	0.035	0.109	7%	15%	16%
Std.Err	0.031	0.006	0.018	1%	3%	3%
0-2 cm (n = 14)						
Ave	0.619	0.090	0.361	15%	62%	23%
Std.Dev	0.223	0.039	0.123	4%	17%	17%
Std.Err	0.060	0.011	0.033	1%	4%	5%
2-5 cm (n = 12)						
Ave	0.469	0.063	0.277	14%	62%	24%
Std.Dev	0.149	0.027	0.089	6%	18%	19%
Std.Err	0.043	0.008	0.026	2%	5%	6%
> 5 cm (n = 10)						
Ave	0.494	0.062	0.307	14%	62%	23%
Std.Dev	0.132	0.030	0.095	10%	12%	13%
Std.Err	0.042	0.009	0.030	3%	4%	4%

3.2.4 Summary

Water phosphorus concentrations were only 20% of the levels reported during the 1980s and data collected during this two-year study suggest that they may still be declining. Phosphorus concentrations in the water were highest during the warmer months that coincide with the period of greatest biological activity. This was true of total, soluble-reactive and biologically-available forms of phosphorus. The concentration of total dissolved P appears to be greater than soluble reactive P (about 1.5 times > during spring 1995). Biologically-available P was always greater at Bacon Dr. than at Spear St..
At both sites, approximately two-thirds of the sediment P was released by acid dissolution and was considered to be inorganic and mineralogically bound. The remaining one third of the sediment P was nearly evenly split between an organic fraction and NaOH-extractable P, of which the latter is generally considered biologically available.

3.3 PHOSPHORUS FLUXES BETWEEN COMPARTMENTS

While monitoring seasonal changes in standing stocks provides valuable information about P retention in streams, it does not identify pathways of P exchange between compartments or the magnitude of these fluxes. It also fails to reveal processes that retain P for shorter periods than a season. By using radiotracers of P in the laboratory, conducting adsorption-desorption experiments with sediments and phosphate, and suspending litter bags in the stream and observing their loss of P through litter decomposition, we were able to quantify some of the more important P fluxes in the LaPlatte River. Because we were principally interested in mechanisms removing P from the water (and because our resources were limited), the majority of our studies involved adding labelled or unlabelled phosphate to water and quantifying its movement to other stream compartments. Radiotracer results were extrapolated back to the stream, and expressed as mg P transformed per m^2 of reach per day. Because the adsorption/desorption experiments were conducted in a shaken centrifuge tube, extrapolation back to the field condition was not attempted.

3.3.1 Phosphate Uptake by Epilithon

Phosphate flux to epilithon was measured in Summer 1994 (~48 h after a storm), again in Fall 1994, and finally in Spring 1995 (Table 3.19). The Summer 1994 and Spring 1995 measurements were made using rocks from Spear St. only, while the fall 1994 study used rocks from both sites. For summer 1994, the average areal phosphate-P uptake rate (per m^2 of rock surface) for epilithon on Spear St. rocks was 66 (±10; 1 SE) mg $P/m^2/day$. The adsorption control for this experiment (no rocks) showed < 1% ^{33}P depletion over 5 hours; in contrast the killed control (autoclaved rocks) had an uptake rate of 29 mg $P/m^2/day$.

Thus about 43% of epilithic uptake appeared to be abiotic (probably a combination of adsorption onto the mucilaginous epilithon matrix and associated silts and clays). Approximately 80% of the bottom at the Spear St. site provides substrate for epilithon. Hence phosphate-P uptake per unit stream area due to epilithon at this site was about 53 mg $/m^2/day$ during Summer 1994.

During Fall 1994, phosphate-P uptake rates for Spear St. rocks were about an order of magnitude lower than during the previous summer (mean = 8 (± 1) mg $P/m^2/day$, expressed relative to rock surface area). Epilithon at the Bacon Dr. site took up phosphate at a greater rate than those at Spear St., 17 (±3) mg P/m^2 of rock surface/day. The killed control for this experiment had a P uptake rate of 2.5 (± 0.3) mg $P/m^2/day$, or about 31% of the total uptake for Spear St. rocks. The Bacon Dr. site provided less substrate for epilithon (39% of the bottom) than Spear St. Thus, when averaged over the reach, phosphate-P uptake was about 6 $mg/m^2/day$ at both the Spear and Bacon sites.

Table 3.19 LaPlatte epilithon ^{33}P uptake. Site = Spear St. or Bacon Dr. Time = season and year. Treatment = description of the local site in the LaPlatte from which the rocks were collected for Summer 1994; the visible amount of epilithon on the rocks for Fall 1994; and the amount of added orthophosphate for Spring 1995. Rate constant = uptake constant normalized to a m^2 of rock surface. BAP = bioavailable P (µg/L), determined by *Selenastrum* bioassay for Summer and Fall 1994 and by Rigler assay for Spring 1995. Flux = P uptake ($mg/m^2/d$).

SITE	SEASON	TREATMENT	RATE CONSTANT	BAP	FLUX
Spear	Summer '94	Slow flow, unshaded	2.144	25	77.2
Spear	Summer '94	Slow flow, shaded	0.943	25	33.9
Spear	Summer '94	Fast flow, unshaded	2.887	25	103.9
Spear	Summer '94	Fast flow, shaded	1.414	25	50.9
Spear	Summer '94	Killed Control	0.834	25	30.0
Spear	Summer '94	Adsorption Control	0.005	25	0.2
Spear	Fall '94	High Biomass	1.633	3	7.1
Spear	Fall '94	High Biomass	1.930	3	8.3
Spear	Fall '94	Low Biomass	0.528	3	2.3
Spear	Fall '94	Killed, High Biomass	0.654	3	2.8
Spear	Fall '94	Killed, Low Biomass	0.427	3	1.8
Bacon	Fall '94	High Biomass	1.693	7	17.1
Bacon	Fall '94	High Biomass	1.804	7	18.2
Bacon	Fall '94	Low Biomass	1.126	7	11.4
Spear	Spring '95	Ambient P	1.298	3	5.6
Spear	Spring '95	Ambient P	1.438	3	6.2
Spear	Spring '95	Ambient + 4μg PO_4-P/L	1.158	7	11.7
Spear	Spring '95	Ambient + 10μg PO_4-P/L	1.579	13	29.6
Spear	Spring '95	Ambient + 20μg PO_4-P/L	2.427	23	80.4
Spear	Spring '95	Ambient + 40μg PO_4-P/L	1.297	43	80.3
Spear	Spring '95	Killed, Ambient P	0.342	3	1.5

The average phosphate-P uptake of 5.6 ($\pm$ 0.3; 1 SE) mg P/m^2/day (per unit rock surface) at the Spear Street site during Spring 1995 was nearly the same as that measured in fall 1994, but only about 12% of the measured uptake at that site after the August 1994 storm. It is interesting that during both the fall and spring experiments, the estimated BAP, which was approximately 3 µg/L, was also only about 12% of the estimated BAP after the August storm. Uptake by the killed control was about 20% of total uptake for Spring 1995. The estimate of phosphate P flux per unit stream bottom at Spear St. for Spring 1995 was 4.5 mg/m^2/day . Addition of orthophosphate to experimental chambers caused an increase in phosphate-P uptake over the phosphate concentration range 2- 25 µg P/L (Figure 3.28). At phosphate-P concentrations $\geq$25 µg /L, phosphate uptake was saturated.

3.3.2 Phosphate Uptake by Macrophytes and Epiphytes

Three sets of microcosm studies were conducted during August and September of 1994 to investigate phosphate-P uptake by macrophytes and epiphytes. While radiotracer was added to the water phase of some microcosms and to the sediments of others, there was movement of tracer between water and sediments (^{32}P leaked out of injection holes when added to sediments, and ^{32}P was adsorbed onto sediments when added to water). Therefore, for every experiment, rate constants could be estimated for P flux between both water and plants and sediments and plants. Epiphytes obtain phosphorus only from the water. All of the macrophyte and epiphyte flux studies were done using plants and sediments from the Bacon St. site, as macrophytes were scarce at the Spear St. site.

3.3.2.1 Flux of Phosphate from Water to Macrophytes

Over a three-day incubation period, about a quarter of the ^{32}P-labelled phosphate added to the water phase of microcosms was incorporated into plant tissues (Table 3.20). Estimates of phosphate flux from water to macrophytes (Table 3.21) averaged 0.057 $\pm$ 0.006 (1 SE)

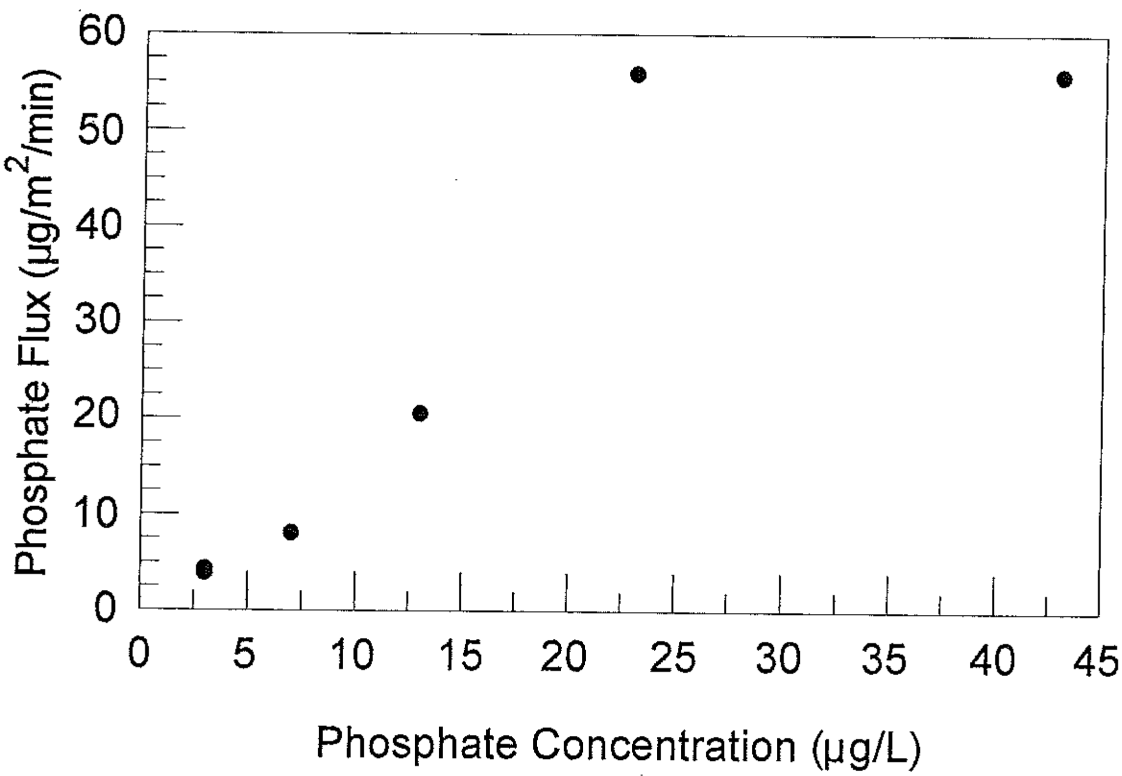


Figure 3.28 Relationship between short-term P uptake by epilithon and added phosphate concentration. (Note: the two ambient P replicates had very similar uptake rates and appear as one point on the graph).

Table 3.20 Percentage of the recovered ^{32}P spike found in each of the major compartments of flow-through microcosms after 3 days incubation. ^{32}P was added either to water or sediment pore as phosphate. Experiment 1 was conducted August 12-15, experiment 2, August 25-28, and Experiment 3, Sept. 14-17. Means and standard errors (in parentheses) are given; for each treatment n=3.

TREATMENT	WATER	SEDIMENTS		TANK WALLS	MACROPHYTES	EPIPHYTES
		BULK	PORE WATER			
Experiment 1- ^{32}P Added to Water*						
Ambient P	36.07 (5.78)	10.05 (0.34)	0.02 (0.00)	5.25 (0.68)	25.53 (4.15)	23.09 (1.10)
Enriched P	49.80 (1.67)	11.73 (0.77)	0.03 (0.01)	3.29 (0.45)	28.18 (0.74)	6.97 (1.19)
Experiment 2- ^{32}P Added to Sediment Pore Water**						
Ambient P	2.38 (0.23)	94.80 (0.05)	0.01 (0.01)	0.21 (0.02)	1.7 (0.28)	0.90 (0.08)
Enriched P	6.36 (2.35)	89.17 (3.81)	0.03 (0.03)	0.17 (0.06)	3.44 (1.26)	0.83 (0.41)
Experiment 3- ^{32}P Added to Either Water or Sediment Pore Water***						
Labelled Water	31.66 (3.09)	5.56 (1.36)	0.04 (0.01)	2.56 (0.30)	28.07 (2.10)	32.11 (2.05)
Labelled Sed.	5.54 (0.32)	85.85 (0.88)	0.08 (0.00)	0.48 (0.16)	4.13 (0.66)	3.91 (0.19)

*In all experiments, the tanks held 73 liters of water. For Experiment 1, there were 4.4-4.9 kg sediment, 2.7-2.9 L of pore water, about 8 g of macrophytes, and 2-3.5 g of epiphytes in each tank.

**For Experiment 2, the tanks contained 5.5-6.5 kg of sediments, 1.5-2.5 L of pore water, about 9 g of macrophytes, and 1-2 g of epiphytes.

***For Experiment 3, the tanks contained 3.1 kg of sediments, about 2 L of pore water, 7-11 g of macrophytes and 3-5 g of epiphytes.

Table 3.21 Phosphorus flux from water and sediments into Bacon Dr. macrophytes during Summer 1994. Specific flux is the product of the rate constant for uptake, K, and the PO4-P available in the tank (=BAP *water volume, for water; =NaOH-P/g)*g sed., for sediments), divided by plant mass. K was determined from the fate of ^{32}P added to water or sediments in flow-through microcosms (n=3) containing plants and sediments (using a numerical model to curve fit). Flux in the stream was estimated as the product of the specific flux and plant mass in the stream (Table 3.19). The first experiment was run August 12-15,the second, August 25-28 and the third, Sept. 14-17. Ambient=untreated water. Enriched=phosphate added to water to increase SRP 5-10 fold.

P SOURCE	TREATMENT	RATE CONSTANT 1/day/g		Available P* mg		SPECIFIC FLUX mg/g/day		FLUX IN STREAM mg/m²/day	
		MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
Experiment 1- ^{32}P Added to Water									
Water	**Ambient P**	0.037	0.004	1.53	0.00	0.057	0.006	9.77	1.10
	Enriched P	0.027	0.000	38.03	0.00	1.014	0.013	172.69	2.16
Sediment	**Ambient P**	0.004	0.001	79.52	16.85	0.028	0.011	4.74	1.91
	Enriched P	0.003	0.000	84.11	3.86	0.025	0.004	4.21	0.68
Experiment 2- ^{32}P Added to Sediment Pore Water									
Water	**Ambient P**	0.046	0.005	2.41	0.00	0.112	0.013	19.01	2.15
	Enriched P	0.022	0.006	31.61	0.00	0.695	0.190	118.41	32.29
Sediment	**Ambient P**	0.0002	0.0002	99.90	11.00	0.015	0.015	2.53	2.53
	Enriched P	0.0000	0.0000	117.80	3.53	0.000	0.000	0.00	0.00
Experiment 3- ^{32}P Added to Water or Sediment Pore Water									
Water	**Labelled Water**	0.033	0.003	0.88	0.00	0.029	0.003	4.97	0.43
	Labelled Sed.	0.038	0.005	0.88	0.00	0.340	0.005	5.72	0.78
Sediment	**Labelled Water**	0.0002	0.0000	56.24	2.15	0.061	0.051	10.36	8.71
	Labelled Sed.	0.0006	0.0006	56.78	1.29	0.032	0.032	5.39	5.39

* Value for sediments assumes that plant roots were in contact with 20% of the sediment volume. For microcosms treated with phosphate, it is assumed that this phosphate did not permeate down to the root zone.

mg P/g dwt/day in mid-August, 0.112 ± 0.013 mg P/g dwt/day in late August, and 0.029 ± 0.003 mg P/g dwt/day in mid-September. If it is assumed that the macrophyte biomass measured at Bacon Dr. in early August was consistent throughout the study period, then the flux of P from water to macrophytes averaged 9.8 ± 1.1 mg P/m^2/day in mid-August, 19 ± 2 mg P/m^2/day in late August, and 5.0 ± 0.4 in mg P/m^2/day in mid September. Phosphate-P uptake rates were much greater in the presence of added orthophosphate than under ambient conditions, indicating that plant uptake of phosphate was not saturated in the LaPlatte River at this time.

3.3.2.2 Flux of Phosphate from Water to Epiphytes

Epiphyte incorporation of radiolabelled phosphate in microcosms was similar to that of macrophytes: one quarter to one-third of the ^{32}P added to the water phase of the microcosms was recovered in epiphytes after three days (Table 3.20). The specific uptake rate of phosphate-P by epiphytes (Table 3.22) was greater than that by macrophytes (Table 3.21): 0.138± 0.020 mg P/g dwt/day in mid-August, 0.275 ± 0.068 mg P/g dwt/day in late August, and 0.062 ± 0.012 mg P/g dwt/day in mid-September. Epiphyte biomass at Bacon Dr. was a little less than macrophyte biomass in August. Nevertheless, the areal uptake rate of phosphate-P by epiphytes exceeded the rate of macrophyte areal uptake by almost two fold: average fluxes for mid-August, late August and mid-September were 17.99 ± 2.61, 35 ± 6, and 8.0 ± 1.6 mg/m^2/day, respectively. Phosphate uptake by epiphytes was enhanced in microcosms enriched with orthophosphate, suggesting that like their hosts, the epiphytes in the LaPlatte were not saturated in their ability to take up phosphate.

3.3.2.3 Flux of Phosphate from Sediments to Macrophytes

Essentially all of the ^{32}P added to microcosm sediments stayed in the sediments over the 3

Table 3.22 Phosphorus flux from water to epiphytes at Bacon Dr.during summer 1994. Specific flux is the product of the rate constant for uptake, K, and the PO_4-P available in the tank (=BAP* water volume), divided by epiphyte mass. K was determined from the fate of ^{32}P added to water or sediments in flow-through microcosms (n=3) containing plants and sediments (using a numerical model to curve fit). Flux in the stream was estimated as the product of the specific flux and epiphyte mass in the stream (Table 3.10). The first experiment was run August 12-15, the second August 25-28, the third, Sept. 14-17. Ambient = untreated water. Enriched = phosphate added to water to increase SRP 5-10 fold. Water is the only source of P for epiphytes.

TREATMENT	RATE CONSTANT 1/day/g		Available P* mg		SPECIFIC FLUX mg/g/day		FLUX IN STREAM** mg/m²/day	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
Experiment 1- 32P Added to Water								
Ambient P	0.090	0.013	1.53	0.00	0.138	0.020	17.99	2.61
Enriched P	0.036	0.012	38.03	0.00	1.357	0.446	176.83	58.13
Experiment 2- 32P Added to Sediment Pore Water								
Ambient P	0.114	0.028	2.41	0.00	0.275	0.068	35.80	8.88
Enriched P-all	0.199	0.179	31.61	0.00	6.290	5.660	588.32	529.19
- w/o outlier***	0.020	0.179	31.61	0.00	0.632	NA	82.41	NA
Experiment 3- 32P Added to Water or Sediment Pore Water								
Labelled Water	0.070	0.014	0.88	0.00	0.062	0.012	8.03	1.62
Labelled Sed.	0.071	0.013	0.88	0.00	0.062	0.012	8.15	1.53

* Value for sediments assumes that plant roots were in contact with 20% of the sediment volume. For microcosms treated with phosphate, it is assumed that this phosphate did not permeate down to the root zone.
** Using the biomass estimate for 8/1/94.
***In one of the microcosms, an extremely high value was obtained for K.

day uptake experiments (Table 3.20). In fact, the ^{32}P content of sediments increased over the course of the experiments because radiotracer lost to the water during the injection process moved back to the sediments. Lack of substantial decreases in the ^{32}P content of sediments resulted in numerical failures during two model runs: i.e., the rate constants for sediment P transfer from sediments to plants could not be calculated (or negative values were obtained). The mean K values calculated in Table 3.21 assume that for these runs, the rate constant was zero. To calculate fluxes from sediments to plants, it was assumed that NaOH-extractable P is a good estimator of the phosphate-P available to plants in sediments. NaOH extractable P includes both phosphate in pore water and that adsorbed onto sediments (as well as P in Fe and Al phosphate compounds). Because phosphate desorption from sediments may be slow, NaOH extractable P probably overestimates available phosphate-P. Mass balance calculations at the end of our experiment indicated that the amount of radiotracer adsorbed onto sediments exceeded that in pore water by 3-4 orders of magnitude (Table 3.20). Thus the availability of sediment P to plants may be controlled by adsorption-desorption kinetics, and biologically mediated adsorption-desorption may proceed at different rates due to microchemical gradients than bulk abiotic adsorption-desorption processes.

Another variable that had to be estimated in calculating plant uptake of sediment P was the sediment volume in the microcosms from which plants could access phosphate. We calculated phosphate uptake fluxes assuming that 20% of the sediment volume was accessible. This figure was based on visual estimates of root extent. It may in fact overestimate the volume occupied, however, as the root mass of the macrophytes was small.

The specific uptake rates obtained for plants extracting P from sediments were similar in magnitude to the flux rates measured for uptake from water. The relative importance of water versus sediment uptake seemed to vary over time. During the August experiments, uptake from the sediments (0.028 ± 0.011 mg P/ g dwt/day for the first experiment and 0.015 ± 0.015 mg P/ g dwt/day for the second) was less than half as great as uptake from water, whereas in mid-September, the estimate of P uptake rate (0.061 ± 0.051mg P/ g dwt/day) exceeded that for water P uptake. Extrapolated to the reach, sediment P uptake by plants was estimated to be in the range of 2-10 mg P/m^2/day (4.7 ± 1.9, 2.5 ± 2.5, and 10.4 ± 8.7 mg/m^2/day in mid-August, late August and mid-September, respectively).

3.3.3 Phosphate Uptake by Sediments

Although the macrophyte microcosm experiments were not set-up with estimation of sediment uptake of P in mind, radiotracer did move from water to sediments. Thus estimates of rates of phosphate adsorption onto sediments at ambient phosphate concentrations could be obtained. These estimates were most reliable when radiotracer was added directly to the water (rather than when it leaked up from labelled sediments and was readsorbed). Assuming that BAP is equal to phosphate-P concentration, the areal fluxes estimated during Experiments 1 and 3 (for ^{32}P added to water) were : 0.68 ± 0.06 and 0.33 ± 0.07 mg/m^2/day, respectively. When SRP concentration was increased to 0.5 mg/L through phosphate addition (Experiment 1), phosphate flux to the sediments increased to 14 ± 1 mg/m^2/day. These findings support the conclusions of the adsorption-desorption experiments (Section 3.3.7): LaPlatte River sediments have the capacity to take up considerably more phosphate when equilibrium conditions are altered.

3.3.4 Phosphate Removal by Detritus

Radiotracer studies of phosphorus uptake by detritus and its associated microorganisms were done in October and November 1994, when detrital burdens in the stream were expected to be greatest (Table 3.23). Our data suggest that during this period,

Table 3.23 Phosphorus flux into different types of CPOM at Bacon Dr.during Fall 1994. Specific flux is the product of the rate constant for uptake, K, and PO4-P concentration, divided by mass or substrate surface area. K was determined from the rate of 32PO4 disappearance from water in beakers containing detritus (n=3). BAP was used as an estimate of PO4-P. Fluxes in the stream were estimated from the product of specific flux and total mass or substrate surface area in the stream (Tables 3.11-3.13; with dead macrophyte mass= .75X the total). Leaf and macrophyte samples were analyzed on 10/14/94 and wood on 11/3/94.

MATERIAL	RATE CONSTANT 1/day		BAP* mg/L	SPECIFIC FLUX mg/g/day		FLUX IN STREAM mg/m²/day	
	MEAN	SE		MEAN	SE	MEAN	SE
Tree Leaves	2.673	1.416	0.004	0.0107	0.0057	0.35	0.21
Dead Macrophytes	8.66	0.435	0.004	0.0346	0.0014	1.29	0.28
				mg/cm²/day			
Wood	0.00139	0.00013	0.012	0.000018	0.000002	0.004	0.001

* SRP rather than BAP was measured. BAP was estimated as 0.1* SRP, as the fall BAP analysis indicated that about one tenth of SRP was bioavailable.

allochthonous leaves removed 0.0107 ± 0.0057 mg P/g dwt/day. Given this rate and the mean CPOM mass on the bottom of the two reaches during the fall sampling (almost all of which was leaves), we estimated that the P flux to stream leaf detritus in early October was about 0.35 mg/m^2/day at both sites.

Macrophyte detritus was better colonized than the allochthonous leaf detritus: for it, the average phosphate uptake rate in early October 1994 was 0.0346 ± 0.014 mg P/g dwt/day. We did not separate dead and live macrophyte material during the fall sampling, but visual estimates suggest that approximately 75% of the macrophyte mass was dead or seriously moribund. If it is assumed that the mass of dead/moribund macrophytes in the Bacon Dr. reach was 0.75 times the estimate of macrophyte biomass, then it can be concluded that macrophyte detritus removed about 1.3 mg P/m^2/day from the water during early October. Uptake of $^{32}PO_4$ by wood was estimated relative to wood surface area rather than wood mass, and was assessed in early November 1994, rather than in October. Uptake rates for wood averaged just 0.000018 ± 0.000002 mg P/cm^2/day. Thus although wood mass was large, its contribution to P uptake was small: 0.004 mg/m^2/day of bottom area in the Bacon Dr. reach and 0.0007 mg/m^2/day in the Spear St. reach.

The overall flux of P into detritus of all types during fall was estimated to be 1.7 mg/m^2/day in the Bacon Dr. reach and 0.35 mg/m^2/day in the Spear St. reach. Over the long term, this P must be released from the detritus as it is decomposed. Some of this decomposition may take place in Lake Champlain if the detritus is washed downstream.

3.3.5 Summary and Synthesis of Radiotracer Studies

All of the flux studies included some work done during Fall 1994 (between September and November) using compartmental components from Bacon Dr. Thus it is possible to examine in an approximate manner the fluxes of P among compartments for this place and time. Some adjustments must be made in the data because macrophyte material (and associated epiphytes) were healthy and taking up P in September, but moribund by the fall sampling in October. Field samplers estimated that 75% of the macrophyte mass was either dead or yellowed in October. Our estimates of detrital uptake of phosphate include uptake onto this dead and dying plant material. Therefore, the values for plant and epiphyte uptake of P obtained in September should be adjusted downward by 75%. Adding the adjusted mean flux rates for plant uptake (1.3 $mg/m^2/day$) and epiphyte uptake (2.0 $mg/m^2/day$) to the estimates for epilithon uptake (6.6 $mg/m^2/day$), decomposer uptake (1.3 $mg/m^2/day$), and sediment adsorption (0.3 $mg/m^2/day$) yields an estimate for total benthic phosphate uptake of 11.5 mg $P/m^2/day$ (Figure 3.29). Most of this uptake was associated with biological compartments (Figure 3.29), but probably included both active uptake and abiotic adsorption onto silts, clays and the periphyton matrix. For the entire 150 m reach, the total daily uptake rate in Fall 1994 was about 21 g P/day. The spiral length for TP is calculated as the ratio of P flux through the reach to P retention within a meter wide band extending across the stream.. For Bacon Dr. in Fall 1994, TP spiral length was estimated to be 5764 m. For BAP it was 481 m.

Because plant and sediment P uptake were not measured at the Spear St.site, we cannot estimate total uptake rates for this site with much reliability. Most likely, uptake by plants was unimportant, however, as plants were very scarce in the reach. Fine-grained sediments covered about 30% of the reach, and were shallower in their depth than at Bacon Dr. If we assume that Spear St. and Bacon Dr. sediments removed P at a similar area

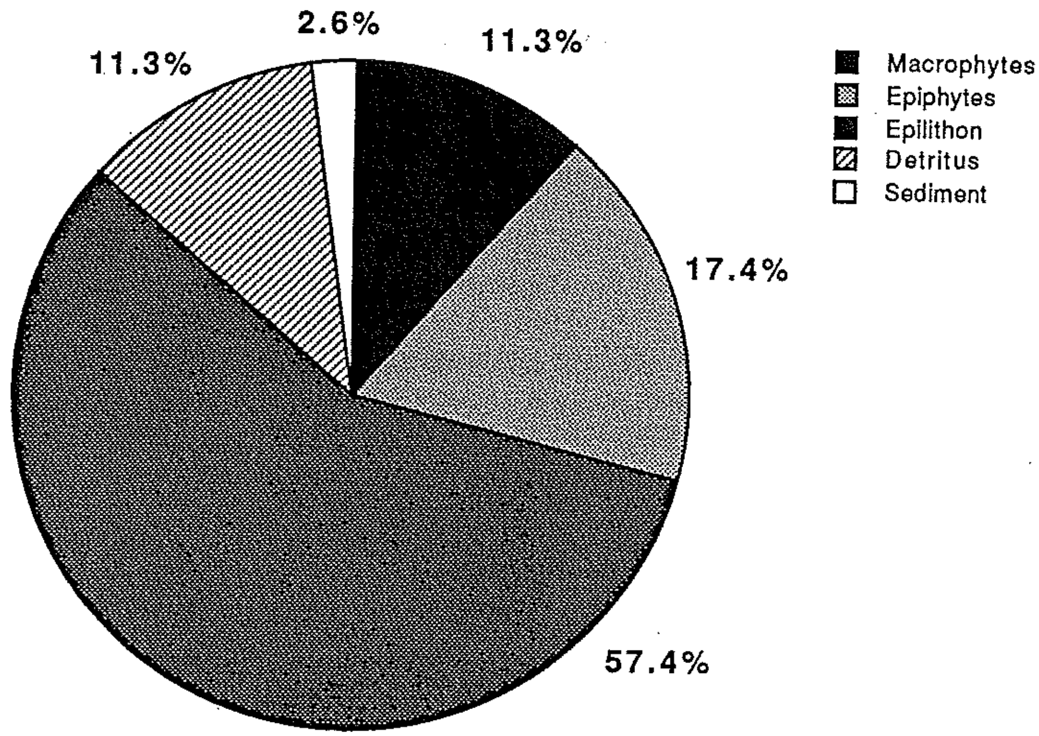


Figure 3.29 Relative distribution of the flux of phosphate from water to stream compartments in Fall 1994 at Bacon Dr. This analysis assumes that 75% of the macrophyte mass present in October was dead.

rates, but the area of removal was 1/3 as great at Spear, then about 0.1 mg P/m^2/day moved from water to sediments at Spear St. Epilithon accounted for a water loss rate of 6.4 mg P/m^2/day and the decomposers took up another 0.35 mg P/m^2/day. Thus the total uptake rate for Fall 1994 at Spear St. is approximated at 7 mg P/m^2/day.

The above estimates of phosphate flux to the stream bottom are not very impressive when compared with the 0.6 and 0.7 kg of SRP that passed through the Spear St. and Bacon Dr. sites on the day of the Fall 1994 sampling (Table 3.3). Just 1 and 3% of SRP was removed at Spear and Bacon, respectively. However, BAP removal was impressive. The Spear St. site removed 11% of the BAP passing through, the Bacon Dr. site, about 30%. Undoubtedly fluxes to the stream bottom are greater in summer: the seasonal studies of P uptake by epilithon at Spear St., and by epipelic algae and macrophytes at Bacon Dr. both showed flux rates 3-8 times higher in summer than in fall. Furthermore, the enrichment experiments demonstrated that the stream's capacity for phosphate uptake is considerable. When "steady state" conditions are disturbed through phosphate additions, benthic uptake rates can increase by many fold. This is the condition that must be considered in interpreting the attenuation study.

3.3.6. P Release from Decomposing Leaves and Plants

Litter bag studies to determine P release from detritus were conducted from September through December, 1994. Litter bags removed from the water were found to contain both decaying litter and an accumulation of organic and inorganic particles. This accumulated debris probably contained the microbial community, which is partly responsible for detrital processing and breakdown, as well as silts and sediments trapped on this community. To determine what was happening to the detritus itself, the accumulated material was removed and examined separately. Following the removal of the accumulated material, the detritus alone was found to decrease exponentially over the time course of the experiment, while the amount of trapped organic and inorganic material present per g of detritus increased (Figure 3.30).

Decay constants were then calculated for the detritus alone. Terrestrial leaf debris tended to decay at a slower rate than aquatic plant detritus, illustrated by mean k values of -0.0019/day in Bacon Dr. and -0.0042/day in Spear St. versus aquatic plant detritus k values of -0.0170 and -0.0192/day for Bacon Dr. and Spear St. respectively (Table 3.24). Detritus in Spear St. was processed faster than that in Bacon Dr. as illustrated by these same decay rates. These rate constants indicate turnover times of 526 and 238 days in Bacon Dr. and Spear St. for terrestrial leaf litter and 59 and 52 days for Bacon Dr. and Spear St. for aquatic plant litter.

The mean P content of aquatic plant debris was higher than that of terrestrial leaf detritus (Table 3.24). Aquatic plant detritus concentrations ranged from 1.95 to 2.19 mg P/g CPOM while terrestrial leaf detritus concentrations ranged from 0.85 to 0.94 mg P/g CPOM. P flux to water from detritus was higher in aquatic plant debris from Bacon Dr., at 1.22 mg P/m^2/day, versus 0.09 mg P/m^2/day from Spear St. Flux from terrestrial leaf debris was higher in Spear St. than Bacon Dr., at 0.12 and 0.06 mg P/m^2/day respectively.

3.3.7 Sediment P Adsorption/Desorption

The results of both the adsorption isotherm study and the adsorption rate study are summarized in Figures 3.31 to 3.33 and Table 3.25. Sediments placed in unspiked distilled water (DW) or filtered river water (FRW), actually released small amounts of P into solution. At the other extreme it is apparent that sediment immersed in solutions with

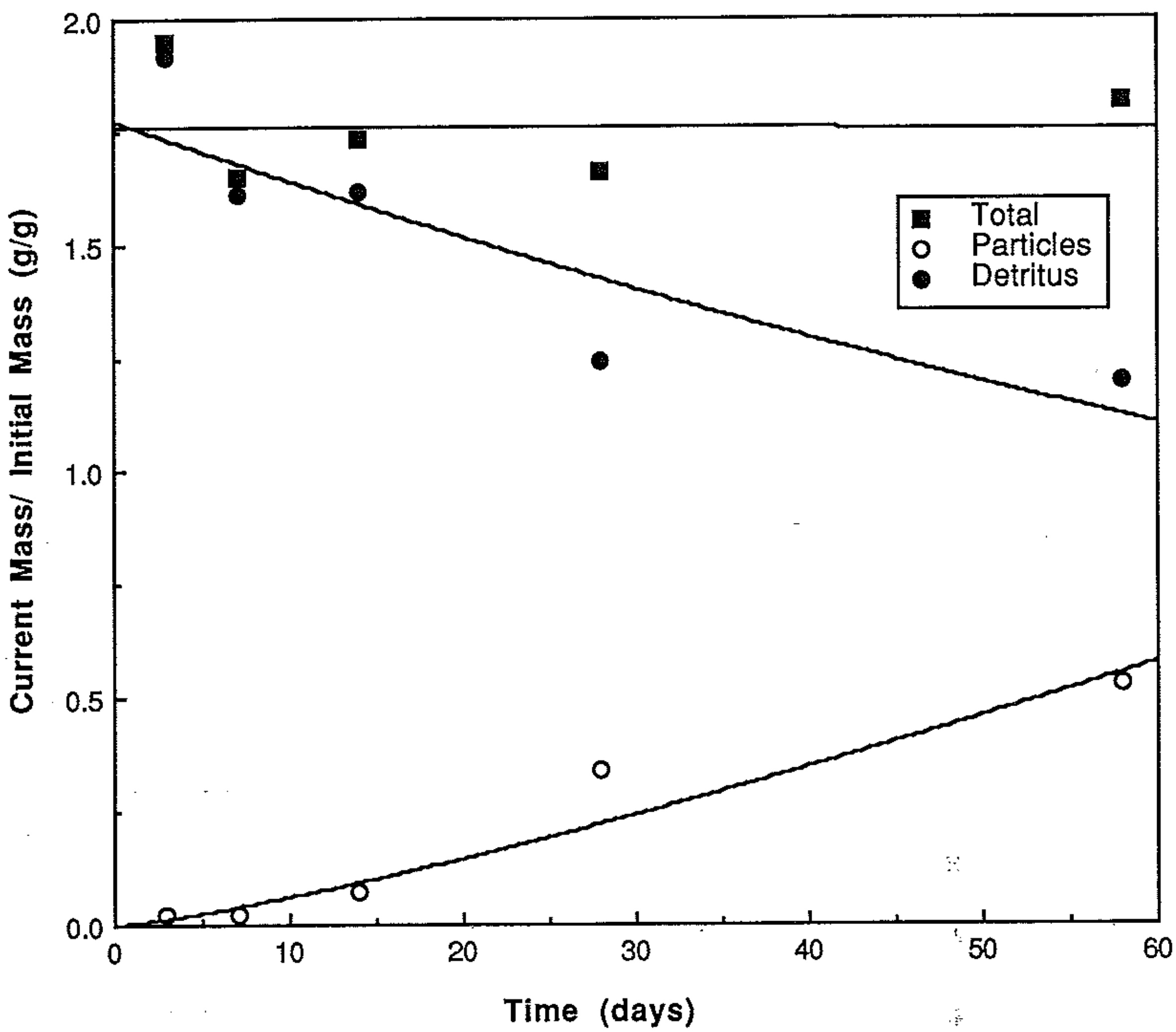
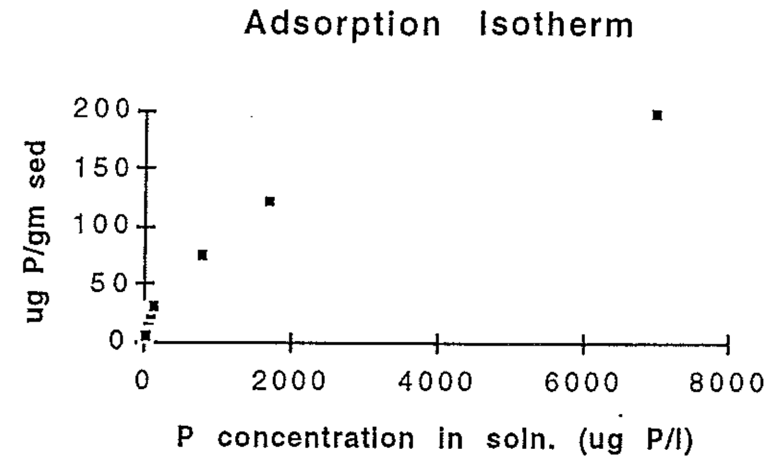


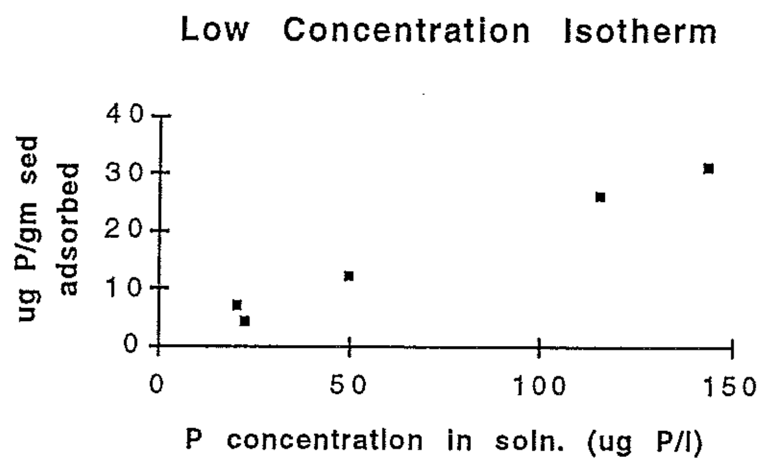
Figure 3.30 Typical time course for decomposition and particle accumulation in litter bags. This example shown is for Box Elder leaves incubated at Spear St. The lines show the exponential regressions of total mass and detrital mass loss vs. time, and the logarithmic regression of particle accumulation vs. time. Particle accumulation is normalized to the mass of the leaf at the time of sampling rather than to initial mass.

Table 3.24 Rate constants, P content and P flux due to decomposition at the two study sites for Fall 1994. P flux to water = -k (P content) mean detrital mass. For terrestrial leaf detritus, mean detrital mass was 32.92 g/m^2 at Bacon Dr. and 32.74 g/m^2 at Spear St. For aquatic plant detritus, detrital mass (36.80 g/m^2 at Bacon Dr., 2.13 g/m^2 at Spear St.) was estimated as 75% of mean macrophyte biomass.

TERRESTRIAL LEAF DETRITUS			
SPECIES	**k 1/day**	**P CONTENT mg P/g CPOM**	**P FLUX TO WATER mg P/m^2/day**
BACON DR.			
Box Elder	-0.0042	0.857	
Basswood	-0.0034	0.950	
American Elm	0.0019	1.005	
Mean	**-0.0019**	**0.937**	**0.059**
SPEAR ST.			
Box Elder	-0.0079	0.710	
Basswood	0.0012	0.875	
American Elm	-0.0059	0.962	
Mean	**-0.0042**	**0.849**	**0.117**
AQUATIC PLANT DETRITUS			
SPECIES	**k 1/day**	**P CONTENT mg P/g CPOM**	**P FLUX TO WATER mg P/m^2/day**
BACON DR.			
Sago Pondweed	-0.0005	1.846	
Floating Leaf Pondweed	-0.0099	1.752	
Elodea	-0.0405	2.255	
Mean	**-0.017**	**1.951**	**1.218**
SPEAR ST.			
Sago Pondweed	-0.0035	2.057	
Floating Leaf Pondweed	-0.0098	2.228	
Elodea	-0.0443	2.295	
Mean	**-0.0192**	**2.193**	**0.09**



i.



ii.

Figure 3.31 P adsorption isotherm of LaPlatte River sediments in filtered river water (i. represents entire concentration range; ii. is a scale expansion of the low concentration range)

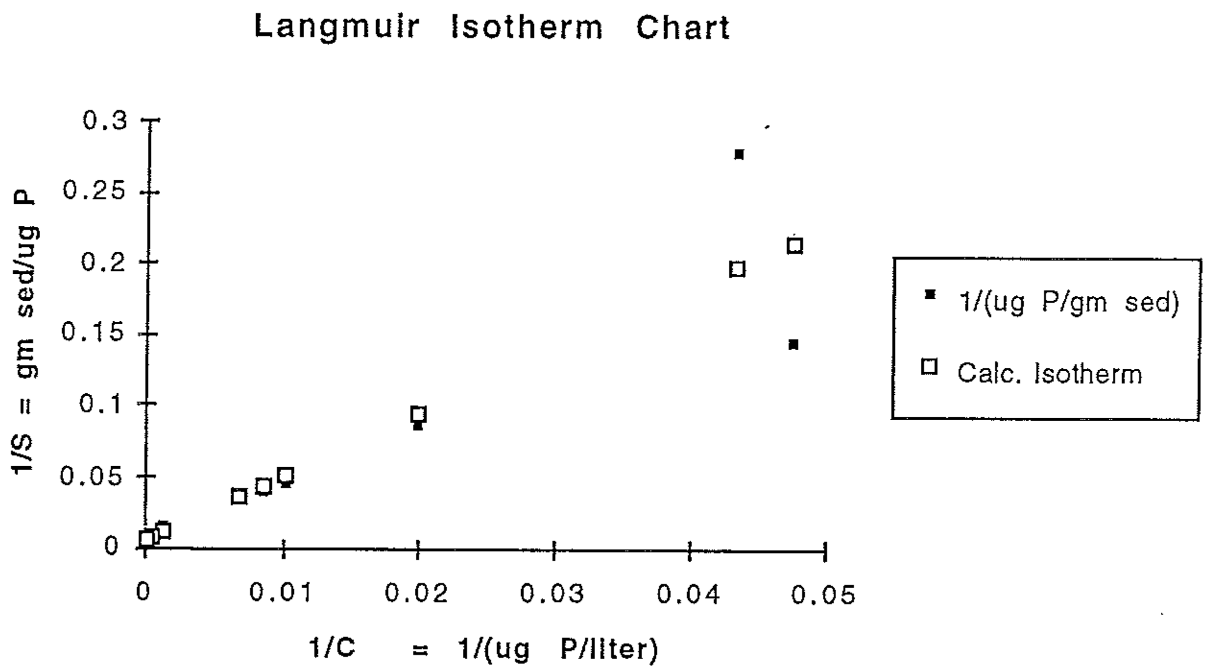
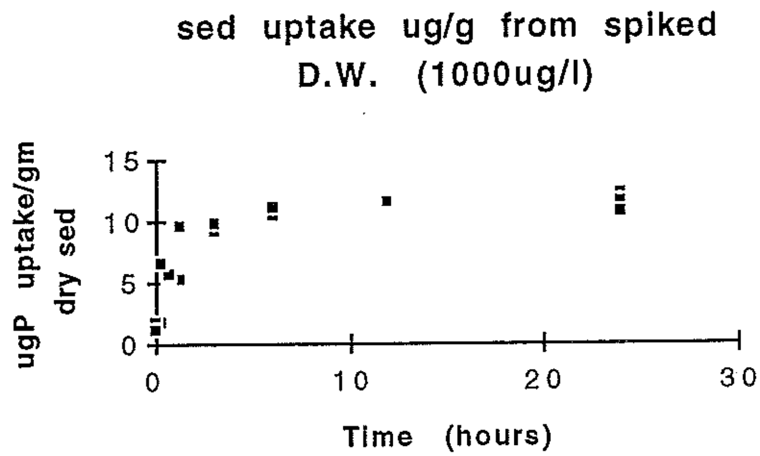
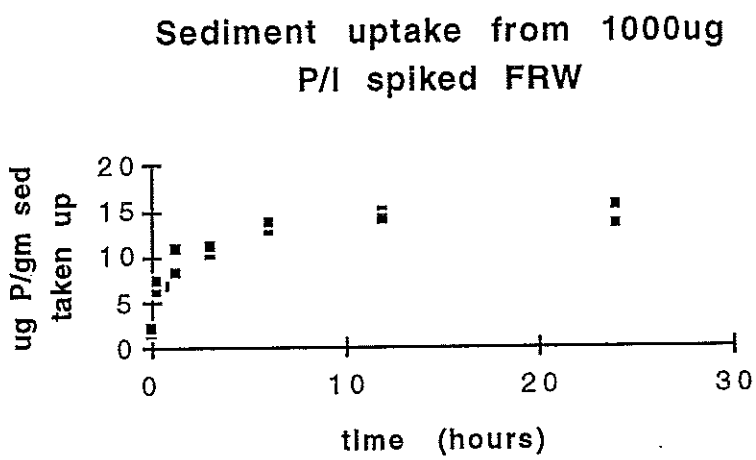


Figure 3.32 Langmuir isotherm for Laplatte River sediments. Solid marks are analytically measured values, open squares are calculated linear regression best fit points.



i.



ii.

Figure 3.33 Rate of P uptake by Laplatte River sediments. (i. uptake from distilled water; ii. uptake from filtered river water).

Table 3.25 Adsorption/desorption isotherm data used in calculating Freundlich and Langmuir isotherms.

Adsorption/Desorption Isotherm Data

Soln	Init. C	Final C	ug P/gm sed ads.	ug P/gm sed rel	net retention
DW	0	58	-0.7	0.6	-1.3
FRW	7	31	-0.3	0.4	-0.7
FRW+100	110	63	0.7	*	*
FRW+250	260	23	3.6	0.4	3.2
FRW+500	520	21	6.9	0.4	6.5
FRW+1000	1000	50	11.6	8.9	2.7
FRW+1500	1500	98	22.4	1.9	20.5
FRW+2000	2000	116	26.3	1.4	24.9
FRW+2000	2000	144	31	0.4	30.6
FRW+5000	5000	800	74	*	*
FRW+10000	10000	1700	121	1.9	119.1
FRW+20000	20000	7000	198	13.7	184.3

* these samples yielded anonomously high values and have not been included in the analysis

high P concentrations can remove substantial quantities of P. In fact, initial concentrations of 20 mg/liter were necessary to begin to approximate saturation (Figure 3.31). These data can be used to quantify the adsorption of P by sediment using either a Freundlich isotherm or a Langmuir isotherm (Figure 3.32). The Freundlich equation is:

$$\mathbf{S = K_F * C^{n} \quad or \quad \log S = Log\ K_F + n \log C}$$

where S = µg P/gm sediment adsorbed,
C = equilibrium solution concentration (µg/l) and
K_F and n are Freundlich adsorption constants.

For this experiment K_F = -.0003 , n = 0.634 with r^2=0.951 for the logarithmic expression.

The Langmuir adsorption equation is :

$$\mathbf{S = S_t\ C/(K_L + C)}$$

where S = µg P/gm sediment adsorbed,
St = maximum adsorptive capacity,
C = equilibrium concentration (µg/l) and
K_L = Langmuir adsorption constant.

For these sediments S_t = 246 µg P/gm sed and K_L = 1088 if adsorption is expressed in ug/gm and solute concentrations unit are µg/liter.

Both Langmuir and Freudlich isotherms suggest that the sediment is far from saturated, and that, if adsorption is an effective process in the fluvial environment, sediments will be an effective buffer to rapidly increasing P loads. This interpretation is, however, based upon P additions as orthophosphate in waters near pH = 7. Certainly adsorption will be affected by the speciation of P and the pH of the surrounding solution, as well as many other external factors. Nevertheless, these values are useful as input parameters into the initial model. Following adsorption, unspiked FRW (7 µg/L P) was added to these sediments to determine what proportion of newly adsorbed P was released when the P concentration of the solution was reduced. Results are equivocal because of suspected contamination of some samples, but they suggest that over the length of the experiment (8 hrs.) more than 90% of adsorbed P remained attached to the sediment. The amount of P released, however, is definitely affected by the concentration of P, and most likely other matrix characteristics of in the surrounding solution. As discussed below in the results of the rate experiment, less P was adsorbed (12 μg/g vs. 14 μg/g) but a larger proportion was re-leased (3 μg/g vs. 1 μg/g) in experiments using DW rather than FRW.

The adsorption rate experiments, in which solutions, either FRW or DW, containing an initial spike equivalent to 1000 μg/L were agitated with sediment for varying time intervals, indicate that equilibrium is reached in approximately 12 hours, and that about half of the total adsorption takes place in less than 1 hour. Maximum adsorption from solutions having an initial concentration of 1000 μg/L ranges from approximately 12 μg P/gm sediment (DW solutions) to 14 μg P/gm sediment (FRW solutions). This is similar to the results obtained during the adsorption isotherm study even though different sediment samples were used. Slight differences between the net adsorption from DW *vs.* FRW may be due to several factors including matrix effects of the supernatant solution or simply the fact that FRW had a higher initial concentration of P (approximately 1100 μg/L vs 1000 μg/L) because of P already in the river water. The relatively high concentration of soluble reactive P in unspiked FRW may be due to the fact that this water was collected just subsequent to an intense rainstorm that occurred after a period of little precipitation. Thus there may have been a pulse of P released during storm runoff. It should be noted that the high concentration of SRP in FRW for this experiment is in marked contrast to the low concentration of SRP in the FRW used during the isotherm experiments which may have resulted from P adsorption to the walls of the polyethylene storage containers. The results of the adsorption rate experiment suggest that during periods of high flow and sediment resuspension there is adequate time to reach adsorption equilibrium. Desorption during a

24 hour period resulted in the release into FRW of approximately 1 mg P/g sediment of the 14-15 μg/g adsorbed during the 24 hour FRW experiments (7%) whereas 3 μg P/g sediment of the 12 μg P/g sediment adsorbed in the 24 hour DW experiment (25%) was desorbed.It is still not known how fast P can diffuse through uppermost sediment layers in order to be adsorbed by deeper material, thus increasing the capacity of the total sediment stock as a reservoir during periods of low flow and little or no sediment resuspension. The notable lack of strong P gradients within these fluvial sediments indicate, however, that the sediments are acting as a single stock, at least to a depth of 8 cm, and not a series of discrete isolated layers.

3.4 ATTENUATION EXPERIMENTS

3.4.1 Winter Low Flow

The first attenuation experiment was conducted in winter (December 20, 1994) when biological activity in the stream (e.g. epilithon uptake, macrophyte growth) is likely to be minimal and physical processes of P cycling (e.g. sediment sorption) predominate, although perhaps at a low rate due to low temperatures. Water temperature was at or near 0° C and most of the stream area was covered by ice and snow. Stream discharge measured during the experiment at Spear St. (the downstream station for the attenuation experiments) was 0.58 m^3/sec (20.6 ft^3/sec) and did not change appreciably over the course of the experiment.

The Rhodamine WT dye (RWT) (1 l) and P (0.89 kg) mixture was added to the river at the Carpenter Road bridge at 0650. Dye was first detected at Spear St. at 1310, 380 minutes later (Figure 3.34). The average velocity for the leading edge of the dye, therefore, was 0.13 m/sec, considerably below the 0.3-0.9 m/sec current velocities observed during discharge measurement. The last detection of dye was recorded at 1700. The initial (essentially instantaneous) pulse of dye spread into a plume that took 230 minutes to pass the end of the reach.

The first detection of P above the background concentration of 0.05 mg/l occurred at 1330, 400 minutes after the addition. Note that the heavy line in Figure 3.34 labeled [TP]' represents TP concentration with background levels subtracted, i.e. the added increment of P. The apparent 20 minute lag between the arrival of the dye pulse and the arrival of the P pulse was probably the result of the lower detection limit for the dye (1 μg/l) compared to that for TP (10 μg/l). The plume of elevated P concentration was considerably more spread out than the dye plume; elevated P concentrations persisted for 830 minutes, more than three times the duration of the conservative dye pulse. It should be noted that intensive sampling ended at 1800, with a final check sample collected at 2240. Because the TP concentration in the final sample was still slightly above background, P concentrations were estimated by linear interpolation from the 1800 value through the value at 2240, and extrapolation of the line until it intersected the original baseline concentration at 0320, December 21. In this manner, the P plume was estimated to last 830 minutes, until 0320 on December 21.

Mass transport of dye and P was calculated by multiplying measured concentrations by the flow volume over the time increment represented by each grab sample. Based on the assumption that the Rhodamine WT was conservative, flow was adjusted so that calculated dye mass recovery was 100%. This standardization amounted to a decrease of about 14% in flow, an adjustment within the potential error range for discharge measurement under ice conditions.

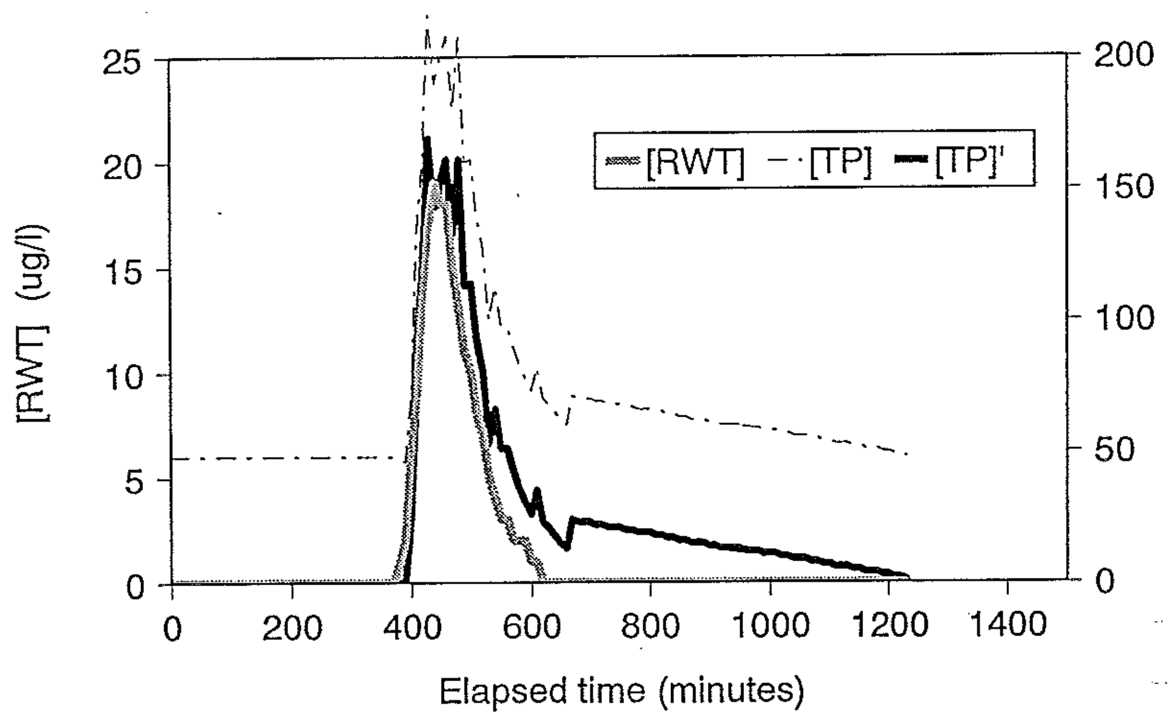


Figure 3.34 Rhodamine dye (RWT), total phosphorus (TP), and background corrected total phosphorus (TP')concentrations at Spear St. during winter attenuation experiment, December 20, 1994. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

Using adjusted flow values, the total P mass measured leaving the reach was calculated to be 827 g, or 93% of the 890 g addition. This represents essentially complete recovery of the added pulse, as the 7% "loss" is within the probable cumulative error of the experimental measurements. Thus, there was essentially no net attenuation of added P observed over the period of the experiment. However, despite the lack of overall attenuation of the introduced P, it is apparent from Figure 3.34 that the P and the dye in the pulse were processed differently because the elevated P concentrations continued for ten hours beyond the end of the dye plume. This is shown more clearly in Figure 3.35, where the ratio of dye to TP is plotted, in addition to the original dye and TP concentrations. The horizontal line represents the theoretical ratio of 0.065, based on the mass of RWT and TP in the original addition; if RWT and TP behaved identically, the observed ratio would equal the theoretical ratio and plot as a straight line.

As shown in Figure 3.35, however, RWT:TP ratios were substantially above theoretical for the first 130 minutes of the P pulse, indicating that less P was passing from the reach than expected. At 1550, the RWT:TP ratio dropped below theoretical, indicating more TP than expected and suggesting release from the reach. When RWT was no longer detected, the ratios became zero and therefore meaningless as an index of P transport.

The ratio was highest in the early portion of the pulse, then decayed in a more or less linear fashion until the dye pulse was past. Thus, the maximum difference between theoretical and observed ratios (maximum retention of P) appeared to occur in the leading portion of the plume, when the concentration of TP, and therefore the gradient between water and sediment, would have been highest.

Considering only the 230 minute duration of the dye plume, a total of 582 g of P was exported from the reach during the passage of the dyes. This represents 65% of the added

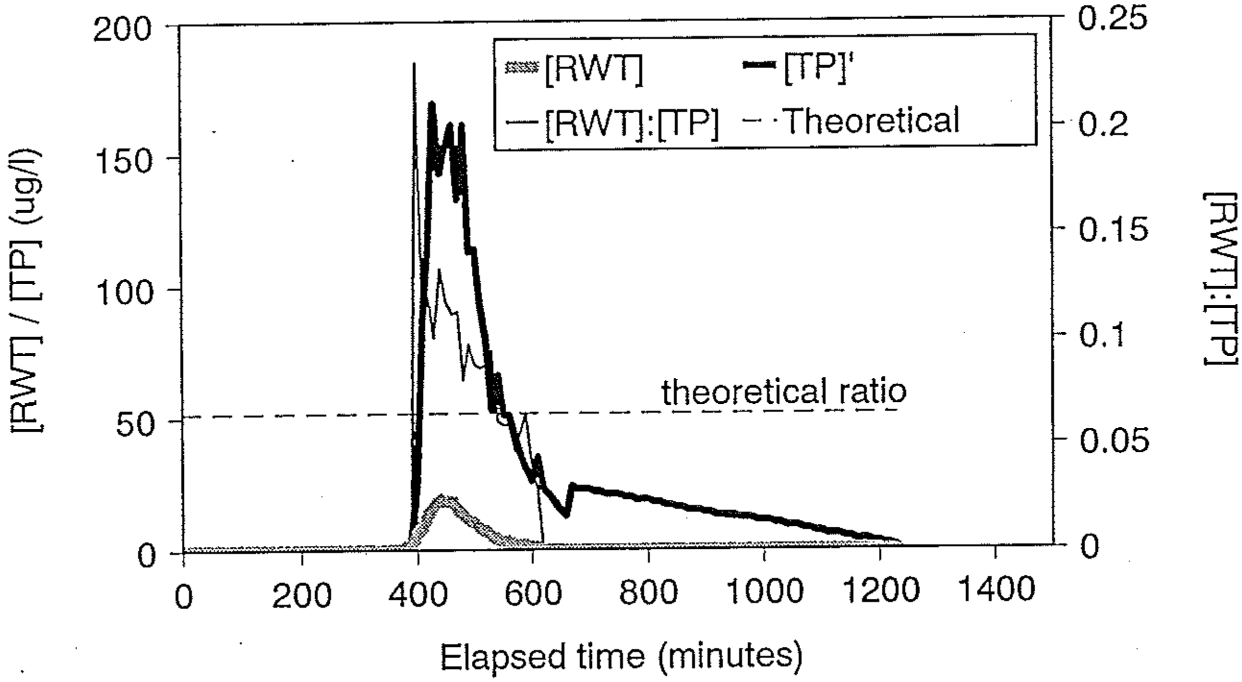


Figure 3.35 Rhodamine dye (RWT), background corrected total phosphorus (TP')concentrations, and dye:phosphorus ratios (RWT:TP) at Spear St. during winter attenuation experiment, December 20, 1994. Theoretical ratio is the ratio of dye to phosphorus in the original addition. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

P and indicates a net short-term retention of 35%, or 308 g of the added P. Assuming an approximate area of the experimental reach of 30,000 m^2, estimated mean P uptake was about 10 mg/m^2 of streambed area, suggesting an average P uptake rate of 0.042 $mg/m^2/min$ over the entire experimental reach. This rate could be as high as 0.06 $mg/m^2/min$ if only the 130 minutes where the RWT:TP ratio exceeded the theoretical value are considered as the operative uptake period. These are probably low estimates of rates, because most of the active "uptake" probably occurred in the first part of the reach where concentration gradients were highest.

The "retention" pattern is shown graphically in Figure 3.36, where the difference between observed and predicted TP transport is plotted. In this graph, predicted TP values were derived by dividing observed RWT export by the theoretical RWT:TP ratio, to yield a prediction of TP export if phosphorus behaved exactly like the conservative dye. Negative values indicate retention of P in the reach. Retention occurred from an elapsed time of 380 minutes to 530 minutes, the same 150 minutes indicated by the RWT:TP ratio (with 20 minutes added at the beginning to account for the initial part of the dye plume when added P was not detected due to low analytical sensitivity). The areas under the negative and positive portions of the line are approximately equal, as shown earlier when 93% of the added P was recovered. The graph also shows that the maximum difference between observed and predicted values (-45 g TP) occurred at 440 minutes elapsed time, roughly concurrent with the highest observed RWT and TP concentrations in the plume, suggesting that the greatest uptake occurred when the concentration gradient between water and potential uptake sites occurred.

Net "uptake" was, of course, very short term; note from the RWT:TP ratios that release of the added P probably began even before the end of the dye plume, when RWT:TP ratios

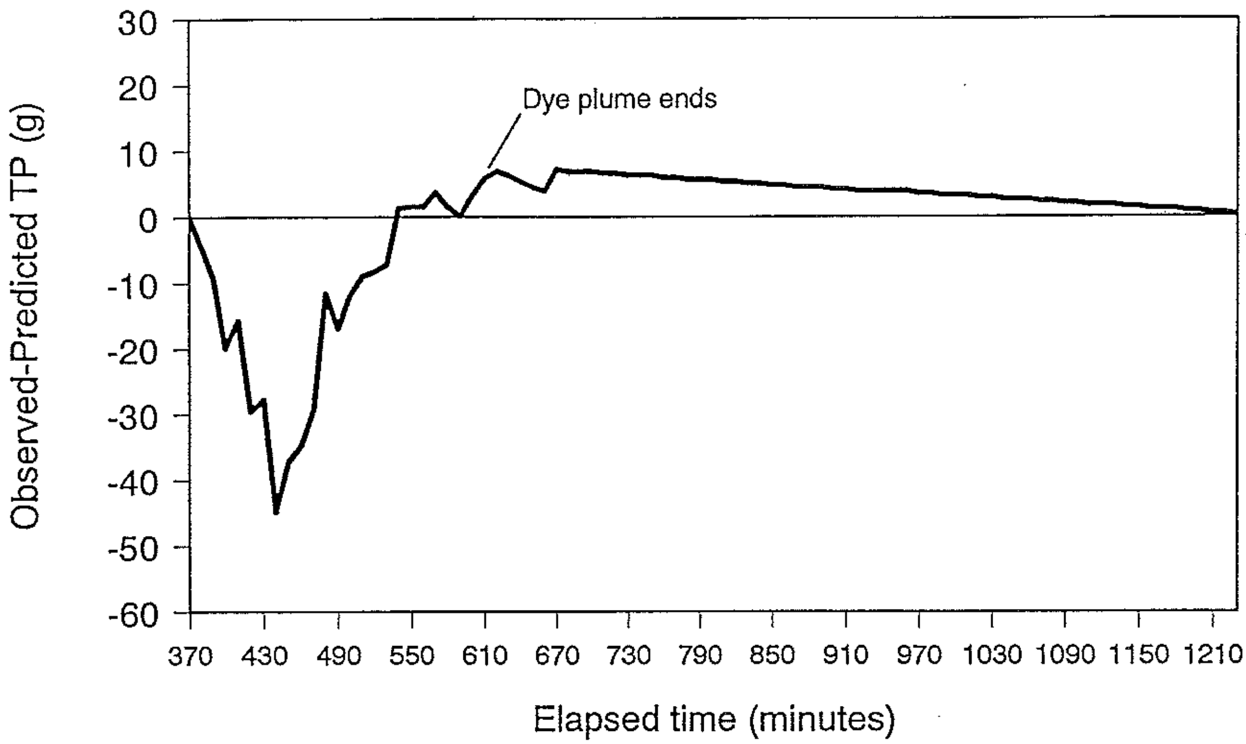


Figure 3.36 Observed minus predicted total phosphorus (TP) export at Spear St. during winter attenuation experiment, December 20, 1994. Predicted TP values were derived by dividing RWT concentrations observed at Spear St. by the theoretical RWT:TP ratio in the original addition. Data plotted during time of phosphorus plume only. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

declined below the theoretical values. Essentially all of the TP was exported from the reach within another 690 minutes. Thus, any apparent P retention lasted only about eleven hours or less under the conditions of the experiment.

3.4.2 Summer Low Flow

The second attenuation experiment was conducted on June 11 -13, 1995 while biological activity in the stream (e.g. periphyton uptake, macrophyte growth) was high. Water temperatures were in the range of 17 - 20 °C. Macrophytes and periphyton were abundant in the reach. Stream discharge measured at Spear St. was initially about 0.25 m^3/sec (9 ft^3/sec), but increased late in the experiment to a high of 0.60 m^3/sec (21.3 ft^3/sec) in response to about 8 mm (0.3 in) of rain that fell from 2300 on June 11 to 0800 on June 12 (NOAA 1995). Stream discharge was about 0.39 m^3/sec (13.7 ft^3/sec) when the experiment ended on June 13.

The combined Rhodamine WT dye (1 l) and P (1.14 kg) were added to the river at Carpenter Rd. at 2320 on June 11. Dye was first detected at Spear St. at 0940 on June 12, 620 minutes after the addition (Figure 3.37). The average velocity of the leading edge of the dye was 0.08 m/sec, substantially slower than the 0.1-0.2 m/sec current velocities observed during discharge measurements, and slower than the average plume velocity (0.13 m/sec) observed in the winter experiment. The last detection of dye was recorded at 1730 on June 12, 1090 minutes after the addition. Thus, the dye plume took 470 minutes to pass by the end of the reach, twice the time observed in the winter experiment.

The first detection of P above the background concentration of 0.082 mg/l occurred at 0940 June 12, concurrent with the first dye. The greater sensitivity of the TP analysis for this experiment improved the detection limit over that of the winter experiment. Again, the

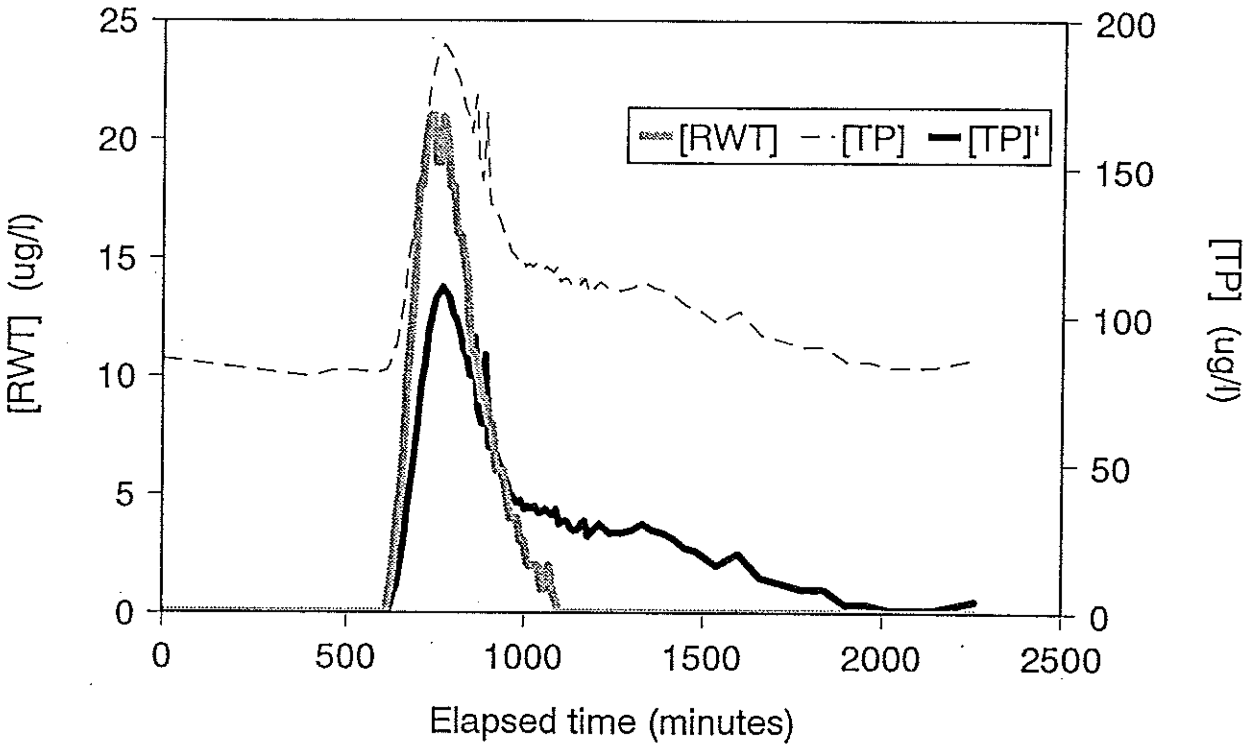


Figure 3.37 Rhodamine dye (RWT), total phosphorus (TP), and background corrected total phosphorus (TP')concentrations at Spear St. during summer attenuation experiment, June 11-13 1995. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

plume of elevated P concentration was more spread out than was the dye. Elevated P concentrations persisted until 1300 on June 13; therefore, the P plume lasted 1640 minutes, three times the spread of the conservative dye pulse. It should be noted that for this experiment, intensive sampling continued until TP concentration returned to background levels at 1300 on June 13 so that extrapolation of the decay of P levels was not necessary.

Mass transport of dye and P was again calculated as the product of measured concentrations and estimated flow over the time increment represented by each grab sample. Discharge was measured four times during the experiment; discharge during the stormflow was estimated by interpolating between the points of measured flow. Flow was again adjusted so that calculated dye mass recovery was 100%; this required an 18% decrease in flow values. The magnitude of this adjustment was probably the result of interpolating through the period of stormflow.

Using adjusted flow values, the total TP mass measured leaving the reach over the 37.7 hours of the experiment was calculated to be 791 g, or 69% of the 1140 g added in the pulse. Thus, there appeared to be a 31% retention of added P in the study reach over the period of the experiment.

As in the winter experiment, the P in the pulse was clearly processed differently from the dye. A similar lag in elevated P concentrations after the end of the dye pulse is apparent in Figure 3.37; this lag lasted nearly 20 hours, compared to 10 hours in December. This is again shown clearly in Figure 3.38, where the ratio of RWT:TP is plotted in addition to the original dye and TP concentrations. The theoretical ratio of 0.0505 (slightly lower than in the first experiment due to the higher P addition) is shown by the horizontal line.

As shown in Figure 3.38, RWT:TP ratios were substantially above theoretical for the first 420 minutes of the dye pulse, indicating the period when less P was passing from the reach then expected. At 1650 on June 12, the RWT:TP ratio dropped below the theoretical, indicating the beginning of net release of P from the reach. As in the winter event, the ratio was highest initially, then declined in an essentially linear fashion until the end of the dye plume. The maximum difference between theoretical and observed ratios (maximum P retention) again appeared to occur in the leading portion of the plume under the strongest P gradient between water and potential uptake sites.

Considering only the duration of the dye plume, a total of 381 g of P was exported from the reach during the 470 minutes required for the dye plume to pass. This represents only 33% of the added P and indicates an initial retention of 66% or 759 g of the added P. About half of this amount (410 g) or 35% of the total addition, can be considered short-term retention because it came out later in the experiment, while 31% (359 g) was retained at the end of the experiment. Again assuming an approximate reach area of 30,000 m^2, estimated initial P uptake was about 25 mg/m^2, about double that observed in the winter experiment. Because the spread of the plume was so much higher in the summer experiment, average P uptake rate was about 0.054 $mg/m^2/min$ over the entire reach, only slightly higher than that estimated for the winter experiment.

The short-term "uptake" pattern is shown in the plot of differences between observed and predicted TP transport in Figure 3.39. Apparent net retention (when observed < predicted) occurs from an elapsed time of 620 to 1040 (when observed > predicted).
Maximum difference between observed and predicted (-40 g TP) occurred over a plateau of about 730-780 minutes elapsed time, concurrent with the highest observed RWT and TP

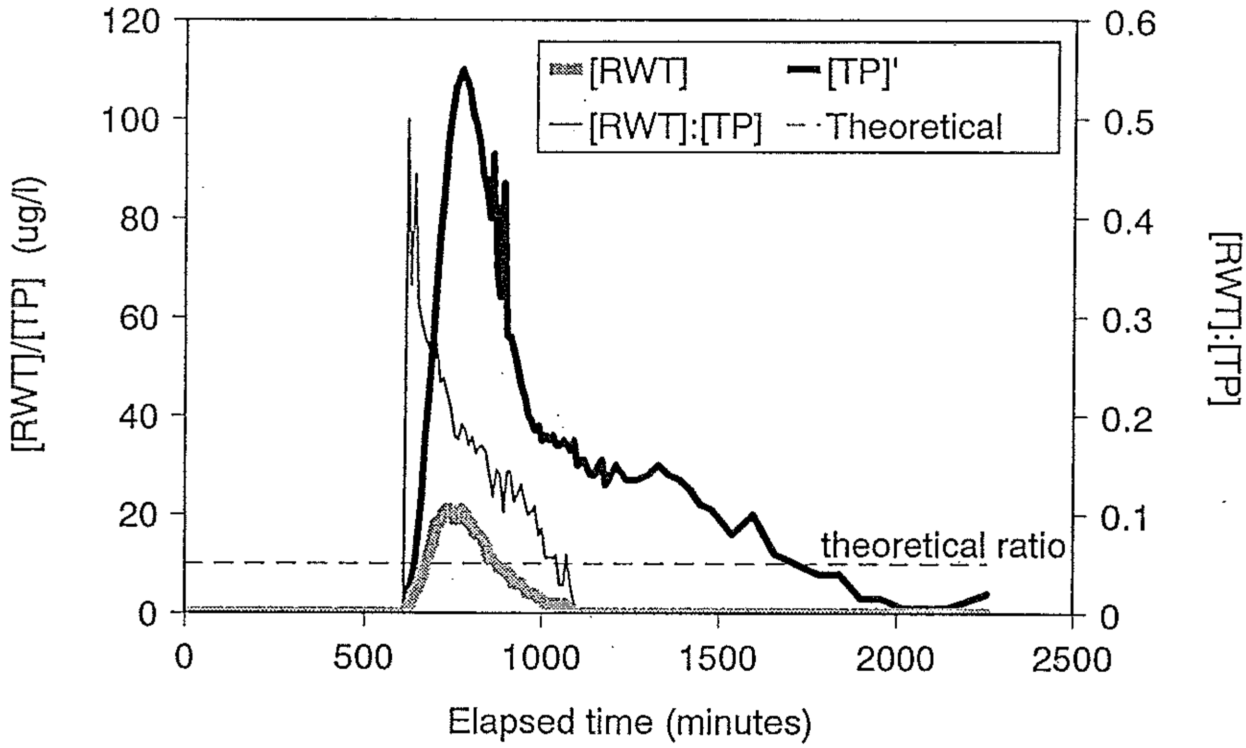


Figure 3.38 Rhodamine dye (RWT), background corrected total phosphorus(TP') concentrations, and dye:phosphorus ratios (RWT:TP) at Spear St. during summer attenuation experiment, June 11-13 1995. Theoretical ratio is the ratio of dye to phosphorus in the original addition. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

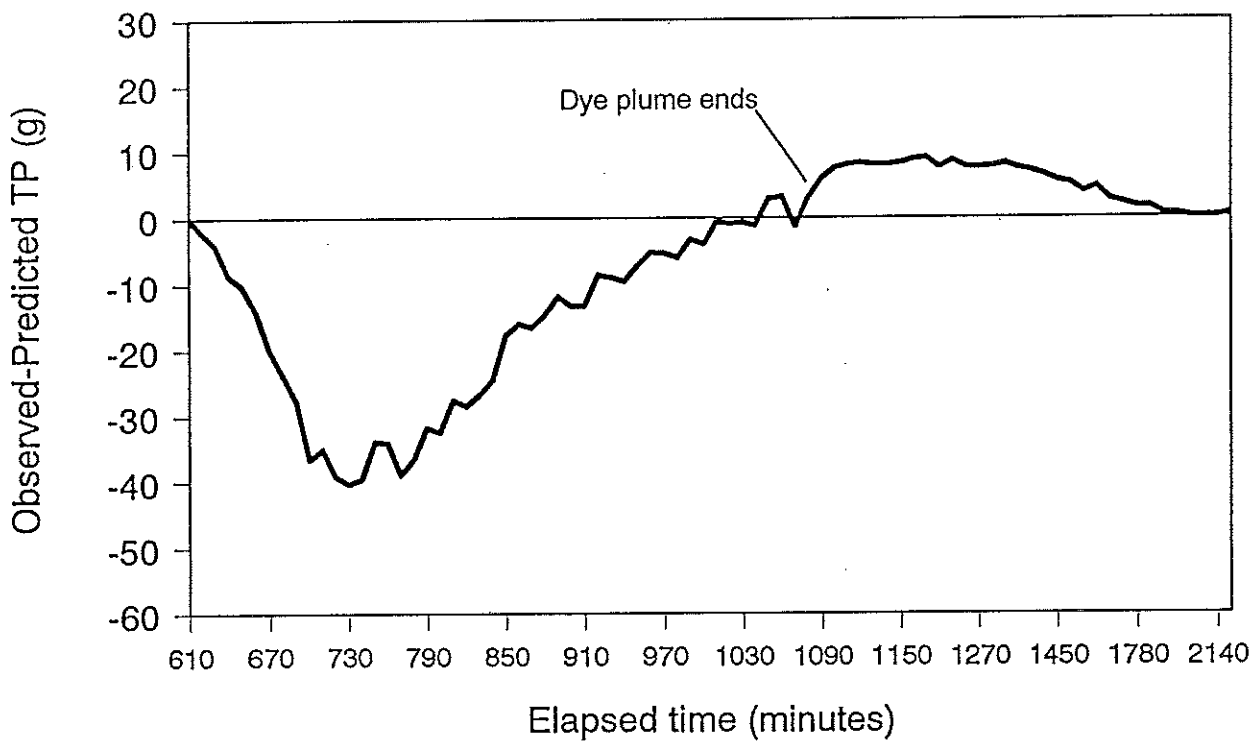


Figure 3.39 Observed minus predicted (TP) export at Spear St. during summer attenuation experiment, June 11-13, 1995. Predicted TP values were derived by dividing RWT concentrations observed at Spear St. by the theoretical RWT:TP ratio in the original addition. Data plotted during time of phosphorus plume only. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

concentrations, suggesting again that the greatest uptake occurred when concentration gradients were highest.

As in the winter experiment, some of this net "uptake" was short-term; release of this short-term retention apparently began about 40 minutes before the end of the dye plume, when RWT:TP ratios declined below the theoretical value, indicating that more TP was passing than predicted. By the end of the experiment, an additional 410 g of TP had been exported from the reach, more than half the short-term uptake of TP.

However, total export of added TP over the duration of the experiment was about 791 g, only 69% of the amount added in the pulse. While the duration of this retention is unknown, it exceeded the short-term retention exhibited in both the winter and summer experiments, as well as the overall 37.7 hour duration of the summer experiment.

This longer-term retention is shown in Figure 3.40, where both observed and predicted (from the RWT:TP ratio) TP export during the attenuation experiment are plotted. The lighter bars in the graph indicate TP retained in the 3 km reach during the passage of the dye plume. As shown previously, some of this P continued to be exported after the dye had passed by. Note also from the graph that the apparent increase in TP export around 970 minutes elapsed time is due not to an increase in TP concentration but to the increase in discharge resulting from the small storm event. The "tail" of this TP export was probably somewhat compressed as TP was transported more rapidly by this surge in flow.

3.4.3 Comparison of the Two Experiments

Despite the different conditions of flow, temperature, and season, the two attenuation experiments exhibited substantial similarity in the behavior of the added dye and P. The two experiments are compared with respect to some principal parameters in Table 3.26. In

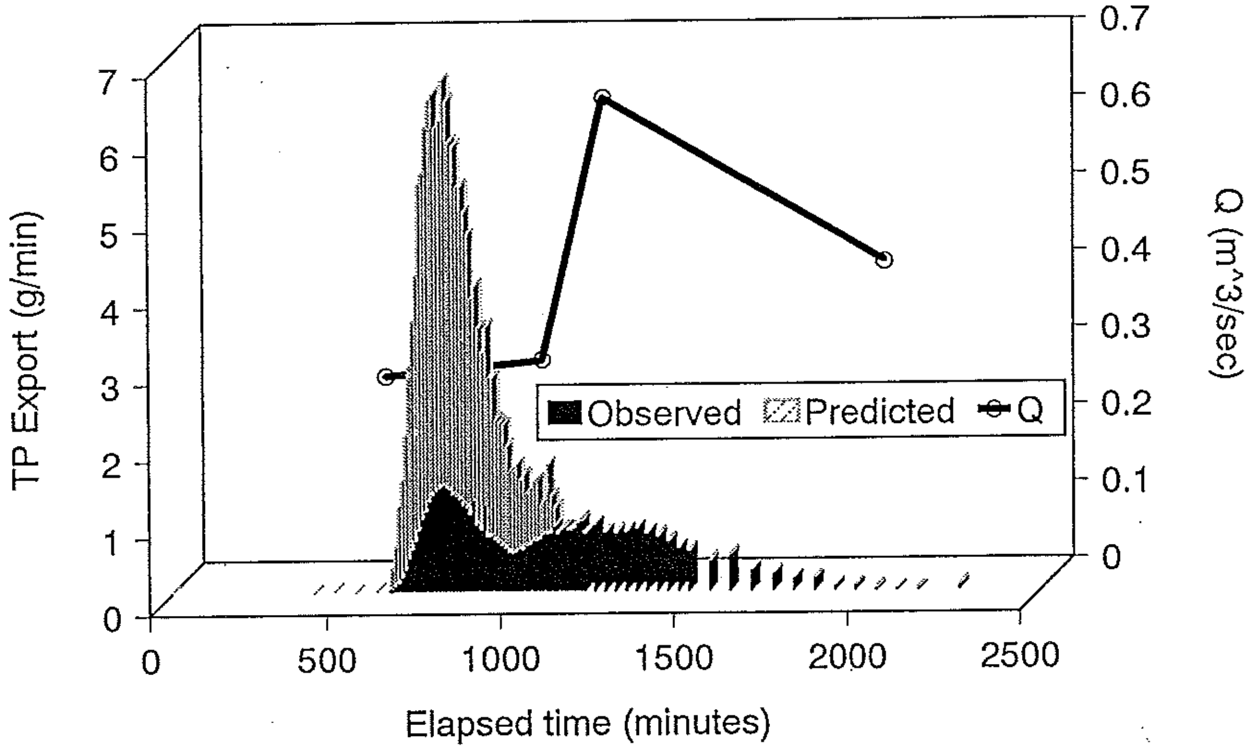


Figure 3.40 Observed and predicted total phosphorus (TP) export at Spear St. during summer attenuation experiment, June 11-13, 1995. Light bars represent TP retained in the 3 km reach during the passage of the dye plume. Predicted TP values were derived by dividing RWT concentrations observed at Spear St. by the theoretical RWT:TP ratio in the original addition. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

Table 3.26 Comparison of Winter and Summer Attenuation Experiments.

	Winter	Summer
Mean discharge	0.57 m^3/sec	0.25 m^3/sec
Water velocity	0.3 - 0.6 m/sec	0.1 - 0.2 m/sec
Plume velocity	0.13 m/sec	0.08 m/sec
Time to RWT	380 minutes	620 minutes
Duration RWT	230 minutes	470 minutes
Time to P	400 minutes*	620 minutes
Duration P	830 minutes	1400 minutes
"Short-term uptake"	308 g (35%)	759 g (66%)
	10 mg/m^2	25 mg/m^2
Mean uptake rate	0.042 mg/m^2/min	0.054 mg/m^2/min
P recovery	93%	69%

*Apparent delay due to analytical sensitivity; see text.

both experiments, both dye and P traveled at an average velocity substantially slower than prevailing current velocities, and plumes of both substances spread out considerably in space and time compared to their instantaneous addition. In both experiments, some initial short-term P retention was demonstrated; this retention was reversible, as at least some was released back into the water over the course of both experiments. Average short-term uptake rates in the two experiments were comparable. The maximum "uptake" of P, defined as the greatest difference between observed and predicted P export, occurred at the time of highest RWT and P concentrations, when concentration gradients between water and some uptake site(s) was highest.

There were, however, some notable differences between the two experiments. Average velocity of the dye plume was considerably lower in summer compared to winter, resulting in a summer time of travel 60% longer than that observed in the winter experiment; this is shown clearly in Figure 3.41. The duration of the summer RWT pulse, i.e. the spread, was nearly double that of the winter addition.

The spread of the P plume was also much greater in the summer experiment than in the winter by a factor of about 75%, as shown in Figure 3.42. Furthermore, the spread of the P plume relative to that of the dye appeared to be greater in summer, suggesting an additional delay of the added P in summer. The plots of observed vs. predicted TP export shown in Figure 3.43 confirm this pattern, showing the longer "tail" of the summer experiment. Short-term P retention in summer, shown in Figure 3.43 , was more than double that observed in winter. The largest difference was, of course, the estimated 30% of added P retained over the duration of the summer experiment, compared to the lack of significant net retention in winter.

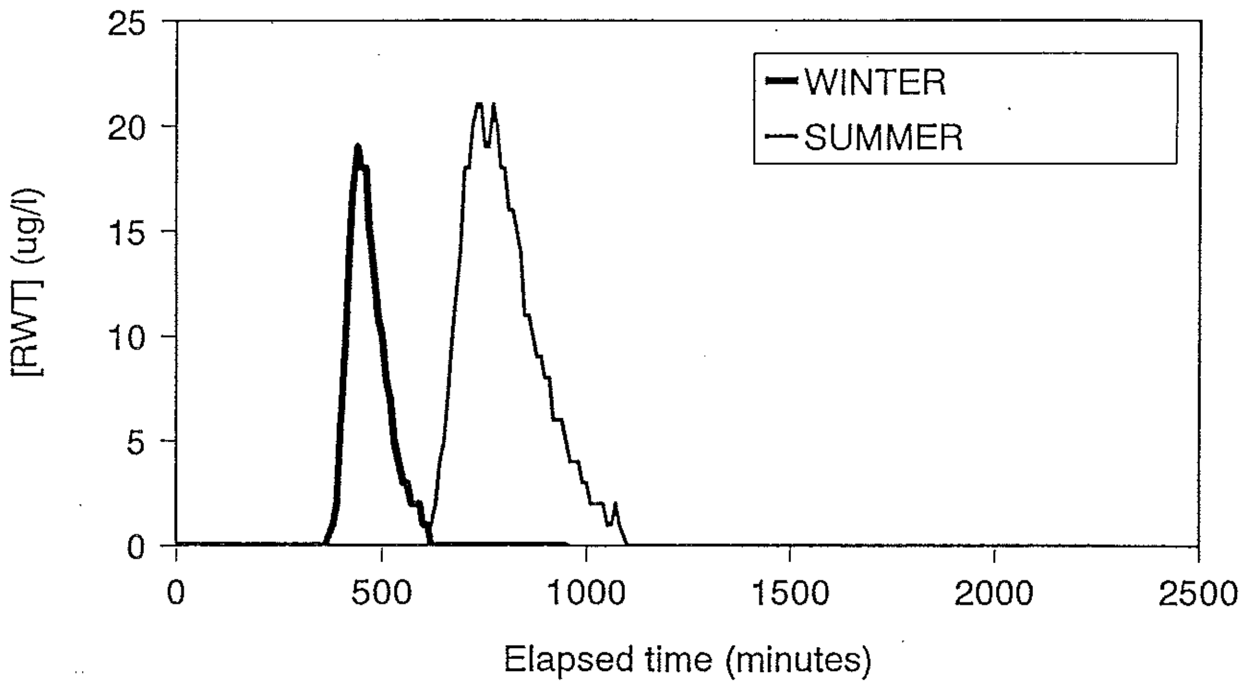


Figure 3.41 Comparison of Rhodamine dye (RWT) plumes at Spear St. during winter (December 20, 1994) and summer (June 11-13, 1995) attenuation experiments. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

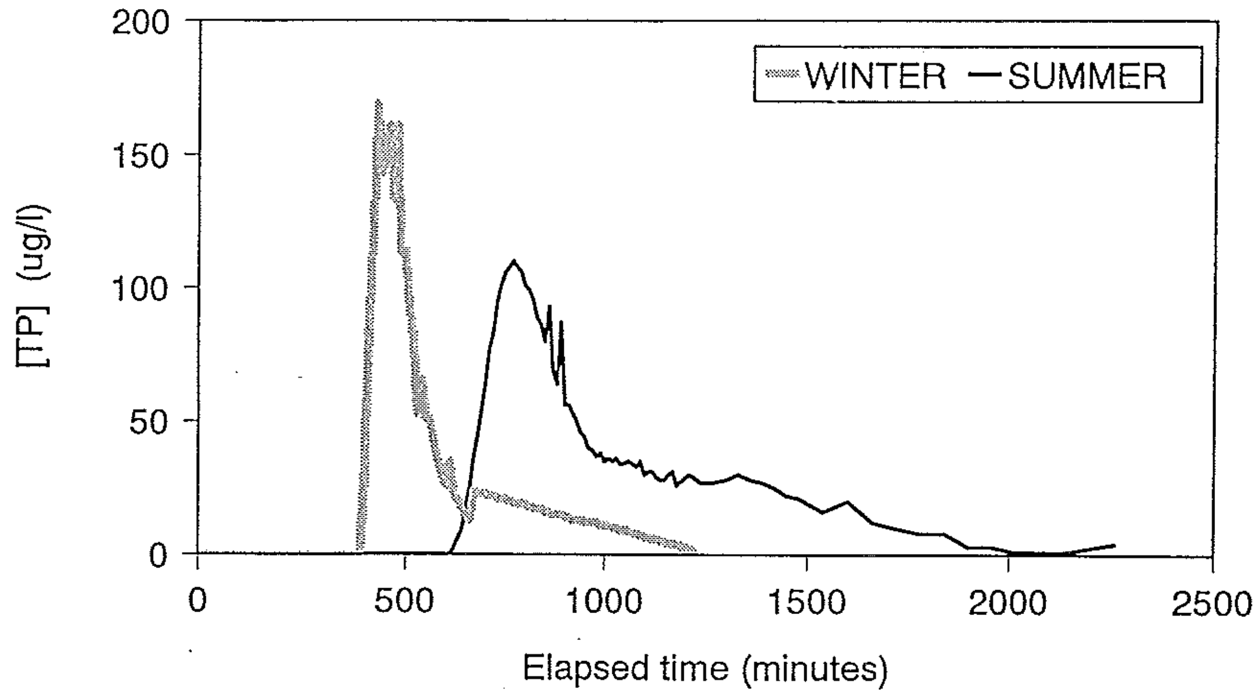


Figure 3.42 Comparison of total phosphorus (TP) plumes at Spear St. during winter (December 20, 1994) and summer (June 11-13, 1995) attenuation experiments. Elapsed time is from time of RWT/TP addition 3 km upstream at Carpenter Rd.

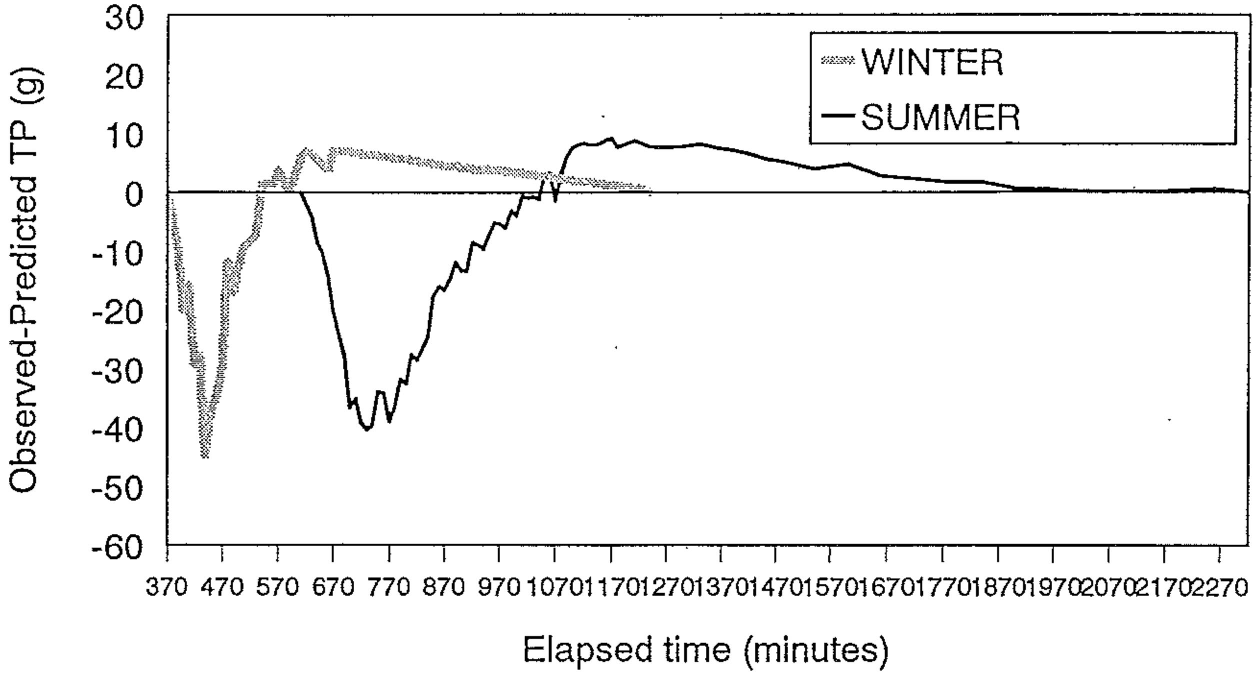


Figure 3.43 Comparison of observed minus predicted total phosphorus (TP) export at Spear St. during winter (December 20, 1994) and summer (June 11-13, 1995) attenuation experiments. Predicted TP values were derived by dividing RWT concentrations observed at Spear St. by the theoretical RWT:TP ratio in the original addition. Data plotted during the time of phosphorus plume only. Elapsed time is from time of RWT/TP addition 3 km upstream at carpenter Rd. Addition took place at time = 0 for both experiments.

3.5 EPILITHON RESPONSE TO N AND P ENRICHMENT

Twenty-eight days prior to the June 1995 attenuation experiment nutrient diffusing substrates were placed in the river at the Spear St. site to ascertain if either nitrogen or phosphorus were limiting to the epilithon (see Section 2.5). ANOVA of the epilithon dry weight that accumulated on the substrates showed no significant N and/or P effect. The mean dry weight per treatment accumulated over the 28 days of this experiment is shown in Figure 3.44 and suggests an average accumulation rate of about 3 g/m2/d over the period.

3.6 MODEL RESULTS

3.6.1 Introduction

The initial version of the DSPM described in this report is an integrated model in STELLA II that describes the dynamics of P cycling, transport and storage in reaches of streams typical of the Lake Champlain Basin. These dynamics can be simulated under conditions of constant or variable input streamflow, under conditions of constant or variable input phosphorus concentrations and during the growing and non-growing seasons. The periods of time over which simulations are typically run can vary from a few hours to several thousand hours (e.g. 1 to approx. 90 days).

The DSPM tracks the dynamics of P cycling, transport and storage in reaches of streams by providing graphical and/or tabular outputs for a wide variety of variables. Additionally, the development of plots of selected variables may be observed on the computer screen during the simulation run itself. The most important DSPM outputs that are used to describe the dynamics of P cycling, transport and storage in reaches of streams include:

1. Comparisons can be made of P concentrations in the streamflow entering the reach to concentrations of P in the streamflow leaving the reach. A difference in P

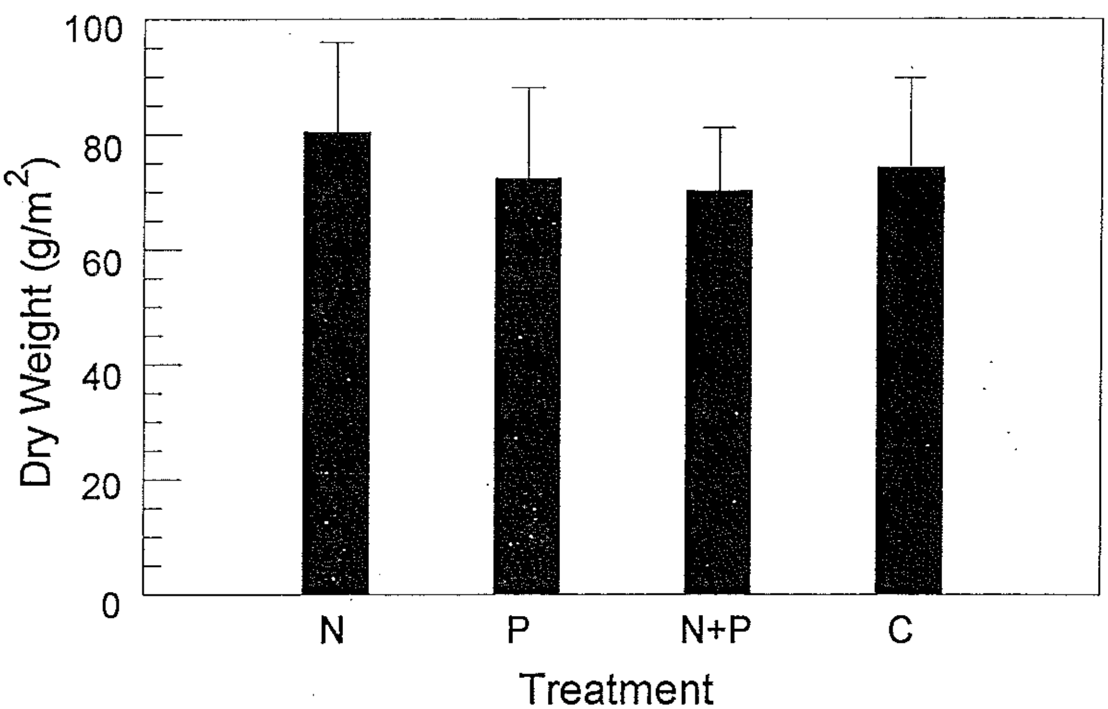


Figure 3.44 Means of epilithon dry weight after 28 days in situ growth on nutrient-diffusing substrates placed at Spear St. (n=4, 1 SE shown). Treatment designations: N = nitrogen enrichment, P = phosphorus enrichment, N+P = both N and P enrichment, C = control (no enrichment).

concentration between the input and output streamflow indicates either a net uptake or net production of P during the time the flow remains within the reach. These comparisons can be made for TP (total phosphorus), SP (soluble total phosphorus) and PP (particulate total phosphorus).

• Compare the inflow DSPM variables (*TP In mgl, SP In mgl, PP In mgl*) to the outflow DSPM variables (*TP Out mgl, SP Out mgl, PP Out mgl*). Note the names of variables in the model are indicated here in italics. For a complete description of them see Appendix, section B.

2. Similar comparison can be made between the input and output mass fluxes of TP, SP and PP. These fluxes are measured in kgP/hr. A difference in P fluxes between the input and output streamflows indicates either a net uptake of P from the water or a net addition of P to the water during the time the flow remains within the confines of the reach.

• Compare the inflow DSPM variables (*TP Inflow kgph, SP Inflow kgph, PP Inflow kgph*) to the outflow DSPM variables (*TP Outflow kgph, SP Outflow kgph, PP Outflow kgph*).

3. If either the concentration or flux of P in the reach input differs from the reach output then the reach has either accumulated P mass from the water or has released P mass to the overlying water as it flows through the reach. The dynamics of P storage within each P storage compartment (the Macrophyte TP, Periphyton TP, Sediment TP, Detritus TP, Water SP and Water PP compartments) can be tracked over the simulation run. Any increase or decrease in the mass of P in any compartment indicates that compartment either accumulated or was a source of P, respectively, over the simulation period.

• Examine over the period of the simulation run the following DSPM variables: *SP Water Mass kg, PP Water Mass kg, TP Pphy Mass kg, TP Mphy Mass kg, and TP Sed Mass kg*. Also examine the DSPM variables:*Sed TP Stand Crop gPpa, Detr TP Stand Crop gPpa, Mphy TP Stand Crop gPpa, Pphy TP Stand Crop gPpa, and Water TP Stand Crop gPpa.*

4. It is also possible to compare the P fluxes that transform and cycle P among the various P storage compartments. Such comparisons can indicate which of the various P cycling mechanisms dominates in controlling changes in the P concentration and P flux between the streamflow input and output. For example, by examining the SP fluxes that increase and/or decrease the SP mass in the *SP Water Mass kg* compartment, it is possible to identify the most important mechanism(s) that may cause SP outputs to differ from the SP inputs.

• Examine over the period of the simulation run the following DSPM variables: *SP Pphy Uptake kgphr, SP Pphy Leak kgphr, SP Mphy Leaf Up kgphr, TP Detri Decay kgphr, SP Sed Desorb kgphr, SP Sed Adsorb kgphr, SP Inflow kgph, and SP Outflow kgph.*

• Also, for example, it is possible to determine whether the sediment is adsorbing SP from the water or desorbing SP to the overlying water. Examine over the period of the simulation run the DSPM variables named *SP Sed Desorb kgphr, and SP Sed Adsorb kgphr.*

Many of the above comparisons are already displayed within the module entitled "Customized Output Presentation" shown on the STELLA II structural diagram in the

Appendix and can be accessed directly. However, through the features of STELLA II, the DSPM also allows the user to access and display the dynamics of the contents of any object (variable) within the structural diagram. It is possible to output graphical or tabular displays of any parameter over the time of simulation and/or to output a relationship between any two variables in the model. To fully access these features of the DSPM the user needs to refer to the Technical Manual for the STELLA II software package (Peterson and Richmond 1993).

The DSPM requires description of each of the six ecosystem components of the model. The following assumptions have been incorporated into the structural development and, therefore, affect model output.

Stream Reach and Channel Hydraulics: The DSPM allows for a wide range of stream flows to be simulated. The input stream flows may be constant over time or may vary to simulate a hydrologic event. A very basic and important assumption of the DSPM, however, is that the volume of water within the reach is completely mixed at all times. That is, the soluble and particulate P compartments behave as ideal complete mix reactors. This simplifying assumption means that this initial version of the DSPM does not perfectly represent reality with regard to the mixing regime typically observed in the stream reaches. Tracer studies on the LaPlatte River, and on other streams and rivers, show clearly that substantial longitudinal gradients in contaminant concentration can exist within a reach due to imperfect mixing. If this condition of non-complete mix within the reach were to be accounted for, the complexity of a DSPM would be very substantially increased. In the creation of the initial version of the DSPM, it was elected not to include the additional complexities to describe incomplete mixing.

The DSPM requires knowledge of the hydraulic characteristics of the stream channel. These hydraulic characteristics are controlled by the physical characteristics of the reach, especially the size and shape of the stream channel, the stream channel slope and the Manning's roughness coefficient. Typically such information is derived from field investigation of each specific reach. Manning equation (Viessman 1989) calculations are made within a previously developed Channel Hydraulic Model (CHM)(Cassell et al. 1995) that define reach specific relationships between flow depth and cross-sectional area of flow, hydraulic radius and average velocity of the streamflow. See Appendix Section D for a detailed description of the CHM model and the methodology used to create these relationships. These derived relationships are then entered as inputs to the DSPM.

The DSPM calculates the average detention time of the reach and the flow and shear velocities that control bedload and suspended load movement through the reach and define the magnitude of periphyton, macrophyte and detrital erosion. As streamflow increases through a reach, the detention time decreases while the velocity of flow increases. Thus, there is less time for organisms to take P from the water and less time for all other reactions to occur. With increasing streamflow, the rates of bedload and suspended load transport and the rates of periphyton and macrophyte erosion increases. The impacts of higher streamflows on P transformation, cycling and transport in a stream reach is profound. The Stream Reach and Hydraulics Module within the DSPM contains the specific algorithms that quantify the above description. The STELLA II structural diagram and documented code listing for this module is provided in the Appendix, sections A and B.

<u>Seasonal Adjustment Capabilities</u>: The DSPM adjusts the various growth rate constants to account for the fact that periphyton and macrophytes grow faster during the warm summer months when there is ample light than during the cold winter months with lower light levels and possible ice cover. Fall senescence of macrophyte growth is also accounted for by

substantially increasing the macrophyte sloughing rate constant during the fall and winter periods, simulating the general structural weakening of macrophyte roots and stems observed during and following active senescence in the fall. Additionally, the DSPM adjusts the diffusion rate constant that controls the rate of P adsorption/desorption in sediments to account for the effect of the change in water temperatures over the annual cycle. Table 2.5. summarizes these adjustment factors. The dates in bold are the warm water, high light growing season while the dates in italics represent cold water, low light winter conditions. March-April is the period of spring emergence and water warming trends while September-October is the fall senescence and water cooling period. The *Algal Gro Adjustment Factor, Macrophyte Gro Adjustment Factor, Detritus Decay Adjustment Factor and the Adsorption Adjustment Factor* in Table 2.5. are at a maximum during the period May through August reflecting warm water and relatively intense lighting conditions. The *Macrophyte Slough Adjustment Factor* is a minimum during this active growing season but is at a maximum when the macrophytes enter senescence and remain dormant during the cold winter months. The *Seasonal Adjust Module* within the DSPM contains the specific algorithms that are used to calculate these adjustments and to identify the time of year during which the simulation run occurs . The STELLA II structural diagram and documented code listing for this module is provided in the Appendix, Sections A and B.

Sediment TP Transformations: The Sediment TP compartment (Figure 2.6) contains, at any point in time, a given mass of sediment (assumed to be particulate matter with diameters less than that of fine sand). Different stream reaches vary in the amount of sediment they contain at any point in time. For example, the stream bottom in riffle reaches typically are lined with cobbles and boulders and there is little space for sediment accumulation as compared to stream reaches (or pool areas) where the streamflow is sluggish and the stream bottom is largely fine sediment.

The mass of sediment associated with the Sediment TP compartment has a certain concentration of TP adsorbed to the particulates that comprise the sediment. As a result of bedload input and bedload output to and from the stream reach both the mass of sediment and sediment TP in the stream reach may accumulate by deposition and/or decrease due to scour. Likewise, the mass of sediment TP and the concentration of the TP contained within the sediment mass in the reach, may vary due to uptake by macrophytes through their roots and by adsorption or desorption reactions which can exchange SP directly with the Water SP compartment.

The adsorption and desorption of soluble phosphorus (SP) by the sediment is assumed to obey the Langmuir Isotherm (McBride 1994). The DSPM assumes that the sediment pore water concentrations of SP are instantaneously maintained according to the Langmuir Isotherm. However, the rates at which SP is transported to Water SP compartment from the sediment (desorption) or adsorbed by the sediment from the Water SP compartment are diffusion controlled as described by Fick's First Law of Diffusion. Desorption and adsorption reactions cannot occur simultaneously.

The DSPM allows sediment mass and sediment TP mass to be moved into or out of the stream reach at the same time as macrophyte growth takes up SP from the sediment and also at the same time that either desorption or adsorption occurs. Thus, neither the mass of sediment nor the mass of sediment TP in the Sediment TP compartment nor the concentration of TP contained in the sediment mass will necessarily remain constant over time, unless the stream reach has reached the condition of steady state or equilibrium. Since these processes also interact with the Water SP compartment, the concentration of SP in the water exiting the reach may also be changed over time.

The Sediment and Sediment TP Transport Module and the Phosphorus Adsorption/Desorption and Diffusion Module within the DSPM contains the specific algorithms that are used to calculate sediment mass, sediment TP mass, sediment TP concentrations at any point in time for the Sediment TP compartment and adsorption/desorption fluxes. The STELLA II structural diagram and documented code listing for this module is provided in the Appendix.

Periphyton TP Transformations: The Periphyton TP compartment (Figure 2.6) also contains, at any time, a given mass of TP. This TP mass represents all the phosphorus, regardless of form, contained within the biomass of the periphyton community. Periphyton tend to grow most readily on stable surfaces such as submerged rocks and plant surfaces rather than on unstable and moving stream bed surfaces, such as a highly mobile sand stream bottom. The physical character of different stream reaches determines how much optimum periphyton habitat may exist in particular reach.

The DSPM assumes the mass of TP in the Periphyton TP compartment is the sum of the growth of periphyton communities on rock surfaces (epilithon) and the leaf and stem surfaces of macrophytes (epiphyton) in the reach. Periphyton growth extracts the bioavailable portion of the SP from the Water SP compartment and incorporates it into the periphyton mass (the Periphyton TP compartment) in accordance with the descriptions of Auer and Canale(1982a and 1982b). The rate at which the periphyton grow is adjusted to account for differences observed over the annual cycle. Additionally, the sticky periphyton mass physically scavenges some particulate phosphorus from the Water PP and Sediment TP compartments. The epilithon are continuously bathed in the moving bedload whereas the epiphytic growth is bathed in the moving stream flow. Thus, the amount of TP in the Periphyton TP compartment is composed of the growth uptake of SP from the Water SP compartment and by the scavenging uptake of PP from the Water PP and Sediment TP compartments.

At the same time, the DSPM assumes the periphyton communities are continuously sloughing off a portion of their TP mass back to the Water PP compartment and into the bedload. Simultaneously, the Periphyton TP compartment is loosing some SP to the Water SP compartment through a leakage mechanism. Additionally, the DSPM assumes that during periods of increased streamflows larger portions of the periphyton growth may be abraded to the Water PP compartment and carried out of the reach as suspended particulates (PP) and to the bedload. Thus, the mass of periphyton and, therefore, the mass of TP in the Periphyton TP compartment is affected simultaneously by all processes that both tend to increase and decrease the amount of TP in the periphyton communities contained in the stream reach. Since these processes interact extensively with the Water SP and Water PP compartments, the concentration of TP in the water exiting the reach may also change over time as a result of periphyton growth dynamics. Additionally, periphyton communities may also influence the accumulation and transport of bedload TP within and through the reach.

The Periphyton Growth and P Uptake Module within the DSPM contains the specific algorithms that are used to calculate periphyton mass and periphyton TP mass at any point in time. The STELLA II structural diagram and documented code listing for this module is provided in the Appendix.

Macrophyte TP Transformations: The Macrophyte TP compartment (Figure 2.6) also contains, at any time, a given mass of TP. This TP mass represents all the phosphorus, regardless of form, contained within the biomass of the macrophyte community. The physical character of different stream reaches determines how much optimum macrophyte habitat may exist in that reach. Macrophytes can grow only in locations where their root system can anchor into the stream bottom substrate. Thus, macrophytes tend to grow out of crevices between submerged rocks in riffly areas of streams and out of unconsolidated stream bed bottoms such as sand, silt etc. The character of the stream bottom is known to influence the character of the macrophyte population. The DSPM assumes mass of TP in the Macrophyte TP compartment is the direct result of the growth of macrophyte communities in those areas of the reach that are designated to be macrophyte habitat. Macrophyte growth extracts soluble P from the Water SP and Sediment TP compartments. The ratio of the soluble P concentration in the sediment pore water to the soluble P concentration in the overlying water is believed to determine the fraction of the P uptake by the macrophytes that comes from the water how much comes from the sediment. This fraction is set at the beginning of the run. The macrophyte TP mass also continuously sloughs off into the streamflow. Additionally, higher stream flows erode even greater portions of the Macrophyte TP mass. A certain fraction of the detached Macrophyte TP mass moves into the Detritus TP compartment and the remainder becomes particulate P in the Water PP compartment. Macrophyte growth and sloughing varies with the season and the DSPM includes algorithms that incorporate the massive fall detachment of macrophytes that occurs upon senescence into the dynamics of P cycling and transport. The Macrophyte Growth and P Uptake Module within the DSPM contains the specific algorithms that are used to calculate both macrophyte mass and macrophyte TP mass at any point in time during the simulation run. The STELLA II structural diagram and documented code listing for this module is given in the Appendix.

Detritus TP Transformations: The Detritus TP compartment (Figure 2.6) contains, at any time, a given mass of TP representing all the phosphorus, regardless of form, contained within the mass of the detritus in the reach. For the purposes of this model detritus is assumed to include only those organic non-woody particulates larger than about 1 cm that are on the bottom of the stream on top of the sediment. The physical characteristic of the stream reach determines how much detritus is available, with faster flowing reaches usually containing less detritus than slower moving reaches.

Detritus TP mass in any given reach is assumed to be the sum of a portion of the Macrophyte TP mass that sloughs and erodes from the living biomass of the Macrophyte TP compartment and from a fraction of the particulate P in the Water PP compartment. The DSPM does not consider the input or output of allochthonous detrital material that typically moves through stream reaches. The detrital TP mass undergoes decay and releases soluble P to the overlying water. The rates of decay are adjusted for seasonal differences. A portion of the Detritus TP is eroded and carried out of the stream reach with the bedload. This erosion increases with higher velocities of the flowing water. The Detritus Phosphorus Module within the DSPM contains the specific algorithms that are used to calculate Detritus TP mass at any point in time during the simulation run. The STELLA II structural diagram and documented code listing for this module is provided in the Appendix.

The Dynamic Stream Phosphorus Model has been used to simulate seven different conditions varying with respect to within channel characteristics, discharge, season and P loading: 1) summer low flow at the Spear St. reach; 2) summer low flow at the Bacon Dr. reach; 3) summer storm flow at the Spear St. reach; 4) a summer P addition experiment along a 3000 m reach with Spear St. characteristics; 5) a winter P addition experiment along a 3000 m reach with Spear St. characteristics; 6) an annual cycle at Spear St.; 7) an annual cycle at Bacon Dr. (Table 3.27). For each simulation a set of specific inputs to the DSPM, comparable to those measured in the field at each of the reaches, defined the nature of the stream reach being simulated, the season of the year, and the concentrations of both soluble P (= SP) and total P (= TP) entering the reach. For each of the simulations only selected figures, illustrative of specific in-stream changes during the simulations are presented. Numerical data defining the DSPM code for initial conditions of summer low flow at the Spear St. reach (simulation 1) are given in the Appendix, Section B. Starting codes for other simulations are available on disk.

Table 3.27 Summary of conditions for DSPM simulations.

Simulation	Reach Type	Season	Flow (Q, cfs)	Input SP (mg/L)	Input TP (mg/L)
1	Spear	Summer	6	0.10	0.14
2	Bacon	Summer	9	0.09	0.12
3	Spear	Summer	1.2/9.2 [a]	0.10/0.18 [a]	0.14/0.22 [a]
4	Spear (3000 m)	Summer	8	0.05/1.85 [b]	0.08/1.88 [b]
5	Spear (3000 m)	Winter	20.6	0.04/1.46 [b]	0.05/1.47 [b]
6	Spear	Annual	3.7/426 [c]	0.03/0.29 [c]	0.05/0.48 [c]
7	Bacon	Annual	3.7/426 [c]	0.03/0.29 [c]	0..05/0.48 [c]

(a) first number is backgound, second number is peak value.

(b) first number is background, second number is background plus P addition (mass of P) diluted by water volume in first 250 m cell.

(c) first number is the minimum value, second number is the maximum value during an annual cycle. Values for Q are from a measured annual hydrograph; TP is calculated as TP = 0.001*Q + 0.05; SP is calculated as SP = 0.06*TP.

The first two simulations (summer simulations at Spear St. and Bacon Dr., respectively) were run under the unrealistic condition of fixed flow and P concentration in order to evaluate the overall behavior of the model. These simulations have a starting day of June 1 and an ending day of August 31. Detailed descriptions of the Bacon Dr. and Spear St. reaches are presented in Section 2.1, Table 3.28, and in the Appendix, Sections C and D. Selected output graphs from the STELLA II software package for these two simulations, and for the moderate summer storm (simulation 3), are included in the Appendix, Section B, following the documented model code. It is important to note the wide range of scale in each of the illustrations resulting from large differences in the size of the different compartments as well as large differences in the amount of change exhibited by individual compartments during a given simulation. Thus while these figures illustrate change in any given parameter during a simulation, careful attention must be paid to scale when comparing one parameter to another. Results of simulations 4 through 7 are presented below. These simulations, the summer and winter P addition experiments, and the annual cycle at Spear St. and Bacon Dr. which incorporate the measured annual hydrograph, were run under more realistic conditions. In general, the DSPM simulations provide output that is in substantial agreement with measured values of corresponding stocks and fluxes.

3.6.2 Results of Model Simulations

The DSPM was used to simulate both the summer and winter P addition experiments to compare model output to field observations. For both seasonal model simulations a reach length of 3000 m was assumed with characteristics similar to Spear St. The reach was then subdivided into twelve sequential 250 m segments, each of which was considered completely mixed. Flow (cfs) for each simulation was set at values measured in the field for the corresponding experiments. A phosphorus pulse was applied to the first segment and completely mixed with the volume of water in this segment to produce an initial concentration comparable to the elevated P concentration achieved during the P addition

Table 3.28 DSPM inputs for defining stream reach.

DSPM Input Parameter	Units	Parameter Value	
		Spear Street	Bacon Drive
Length of Reach m	meters	150	150
Depth Flow vs Q	see relationship in Appendix D		
Avg Vel vs Q	see relationship in Appendix D		
Hyd Rad vs Q	see relationship in Appendix D		
Chan slope	dimensionless	0.0085	0.0025
Width @ LowQm	meters	11.5	14.5
Sed Part Dia mm	millimeters	0.50	0.25
Sed Bulk Den	gram/cu. cm	1.75	1.75
Sed Area Fract	dimensionless	0.07	0.50
Epil Hab Area Fract	dimensionless	0.75	0.35
Mphy Hab Area Fract	dimensionless	0.025	0.825
Sed Init Depth	centimeters	5	5
Wt Fract Fines	dimensionless	0.03	0.10

experiments (see Section 3.4). The output from the first segment became the input for the second segment and continued with successive outputs providing inputs for the adjacent downstream segment. The DSPM predictions of P concentration for the last segment (2750 - 3000 m) during the summer and winter experiments are shown in Figures 3.45 and 3.46, respectively, along with the measured P concentrations.

For the summer simulation, the travel time for the P pulse to reach this final segment was approximately 12 hours compared to 10.3 hours measured in the field . For the winter simulation, the travel time for the P peak to reach this final segment was approximately 5 hours compared to 6.3 hours measured in the field. The peak P concentration in the summer simulation was approximately 0.26 mg P/L compared to 0.19 mg P/L measured during the experiment. For the winter simulation, the peak P concentration was approximately 0.23 mg P/L compared to 0.22 mg P/L measured during the experiment. The simulations suggest that some P was retained within the reach during the summer, primarily due to sediment adsorption and periphyton uptake, whereas during the winter little P was retained. The results of these DSPM simulations of in-stream P attenuations are comparable to field observations suggesting model validity for the reach lengths and time intervals considered (see Section 4.3).

Simulations of an annual cycle (1994) were run for both the Spear St. reach and the Bacon Dr. reach. A measured annual hydrograph was used to estimate the TP and SP concentrations as a function of Q (see Table 3.27). The simulations were run for the period January 1 to December 31. Due to the highly variable nature of the hydrograph, and associated P input to the reach, the output from the DSPM became unstable and chaotic. Chaotic behavior of non-linear dynamic models is commonly observed. In this case it was determined that shortening the time step from 1.0 hour to 0.05 hour was sufficient to produce stable output, however, a significant increase in computational overhead was

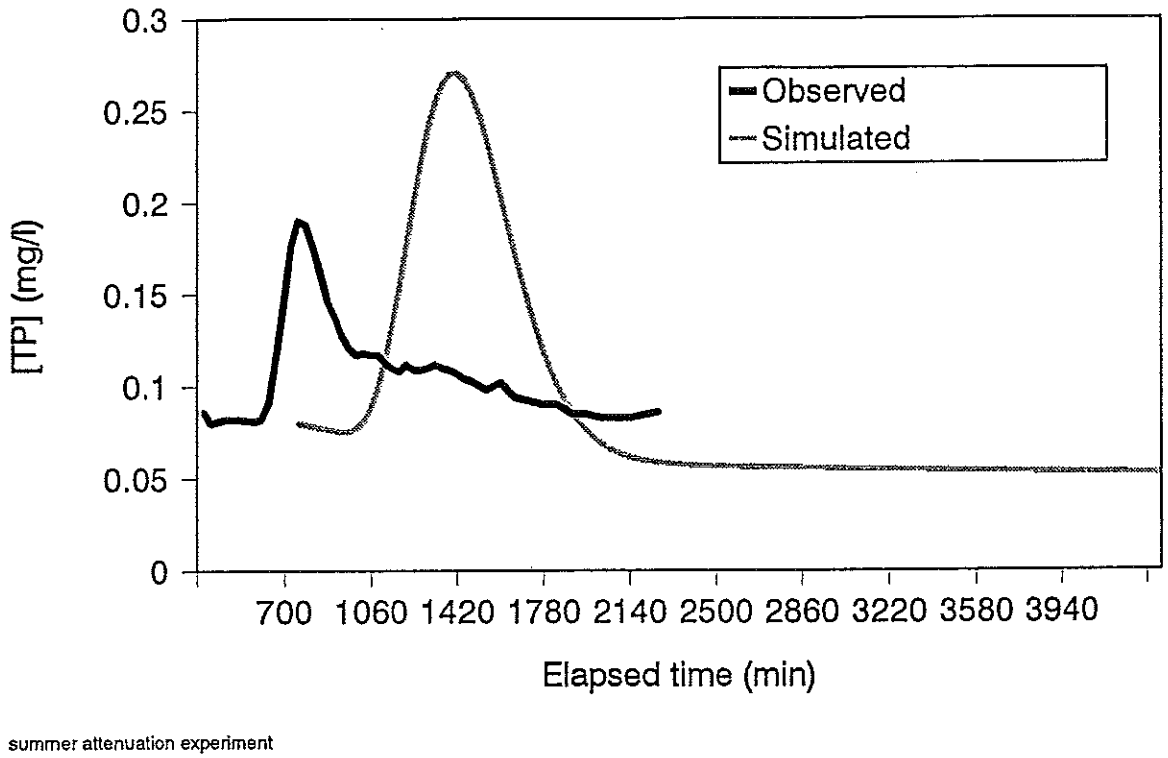


Figure 3.45 Phosphorus pulse observed and simulated during the summer attenuation experiment at the Spear St. site 3 km downstream from the point of release.

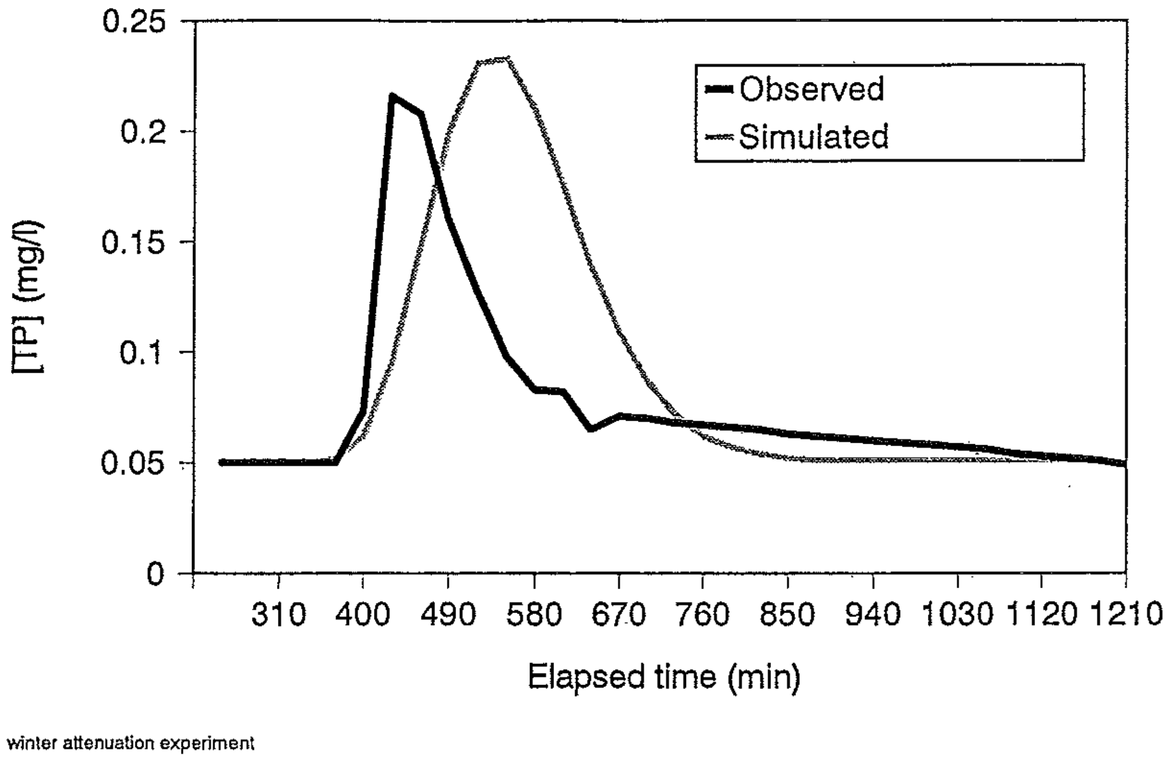


Figure 3.46 Phosphorus pulse observed and simulated during the winter attenuation experiment at the Spear St. site 3 km downstream from the point of release.

incurred. Even on a fast Pentium computer with 32 Mb of memory, CPU time to run a simulation of one month is nearly ten minutes and the short time step inflates the model to nearly 6 Mb. Furthermore, only one month can be simulated at a time due to memory limitations. Despite these constraints the annual cycle at each reach was run by stringing together monthly simulations.

The annual hydrograph and the total P stock at each reach that was predicted by the DSPM are shown in Figure 3.47. The approximately ten fold difference in P stock between Bacon Dr. and Spear St. that was measured in this study (see Section 3.1.6) was realistically reproduced by the DSPM, although the model output was 30 to 40% lower. Given the predominance of the sediment P stock this discrepancy in the model output is likely due to too low an estimate of the areal coverage of sediment in these reaches. The near constancy of the total P stock reflects the dynamic stasis of the dominant sediment stock and its largely invariant P concentration. However, when the scale is expanded the seasonal pattern in the total P stock at both reaches becomes apparent (Figures 3.48 and 3.49). At both Bacon Dr. and Spear St. the model suggests that there is some retention of P within the reach during the summer months followed by a reduction in the total P stock during the fall and winter. However, the amount of variability is small and when net P flux is calculated from the DSPM output it appears that over an annual cycle as much P leaves as enters each reach. The DSPM predicted approximately 6 x 10^3 kg P fluxes through each reach during 1994. The net P flux for Bacon Dr. and the annual hydrograph are depicted in Figure 3.50; the data for Spear St. is quite similar. The graph shows that during moderate flow events of less than 100 cfs there are short periods when P accumulates in the reach (positive net P flux). Larger flow events result in an initial accumulation of P in the reach followed by a flushing out of P (negative net P flux). The mean annual net P flux calculated from the DSPM was positive for Bacon Dr. (+0.2 kg P), whereas the value for Spear St.

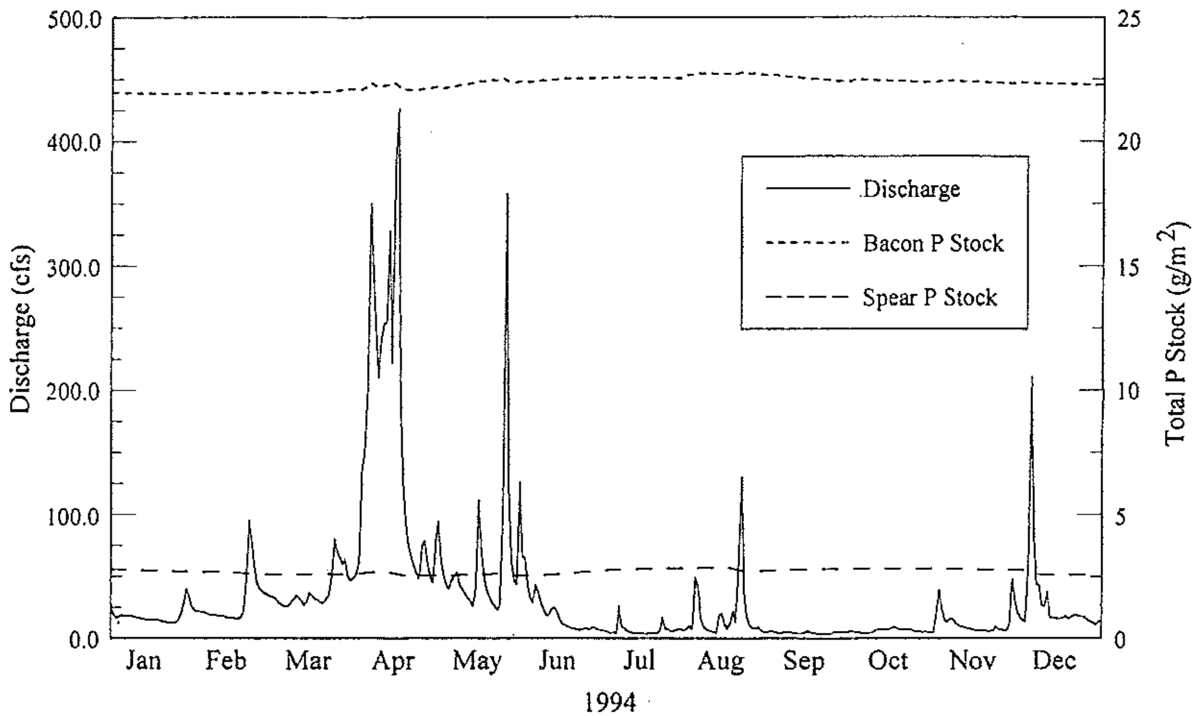


Figure 3.47 Measured hydrograph for 1994 and DSPM predicted total P stock for the Bacon Dr. and Spear St. sites.

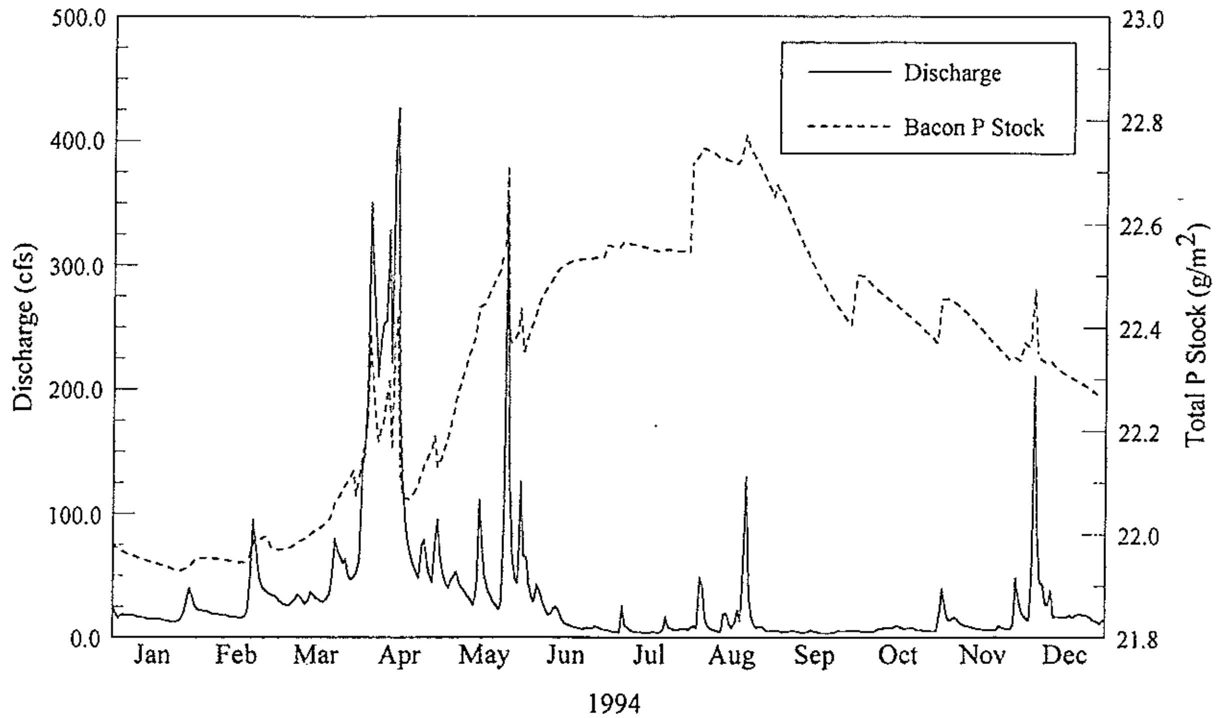


Figure 3.48 Measured hydrograph for 1994 and DSPM predicted total P stock plotted on an expanded scale for the Bacon Dr. site.

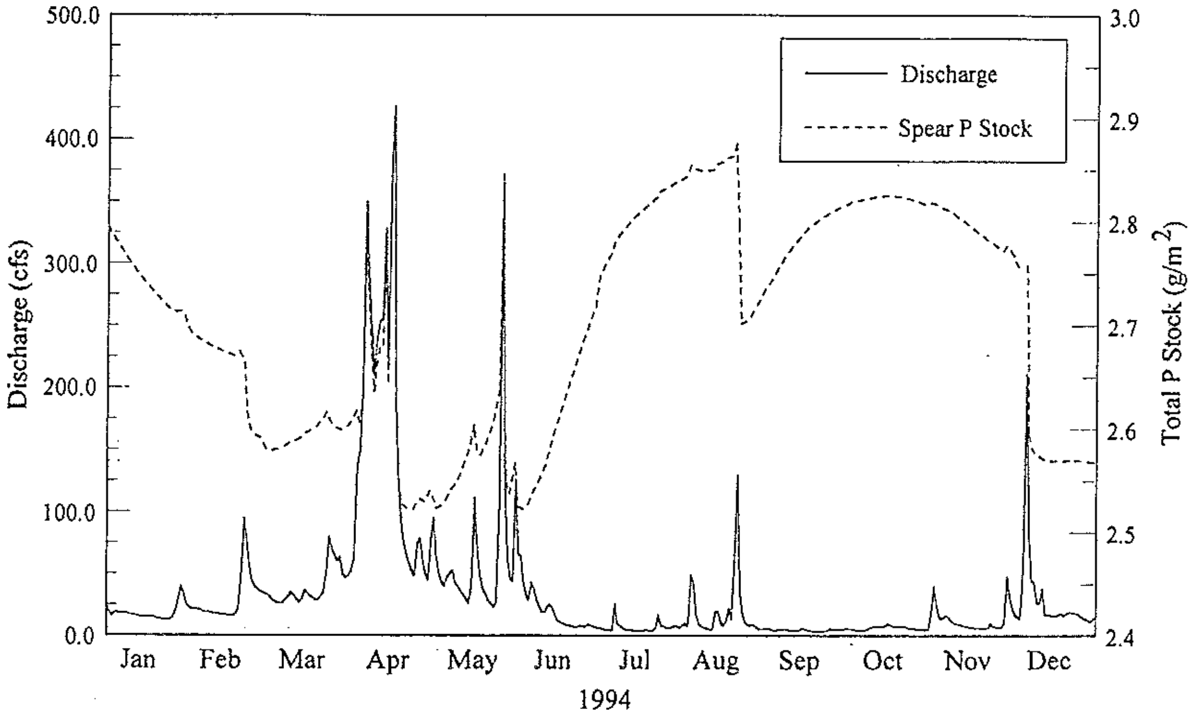


Figure 3.49 Measured hydrograph for 1994 and DSPM predicted total P stock plotted on an expanded scale for the Spear St. site.

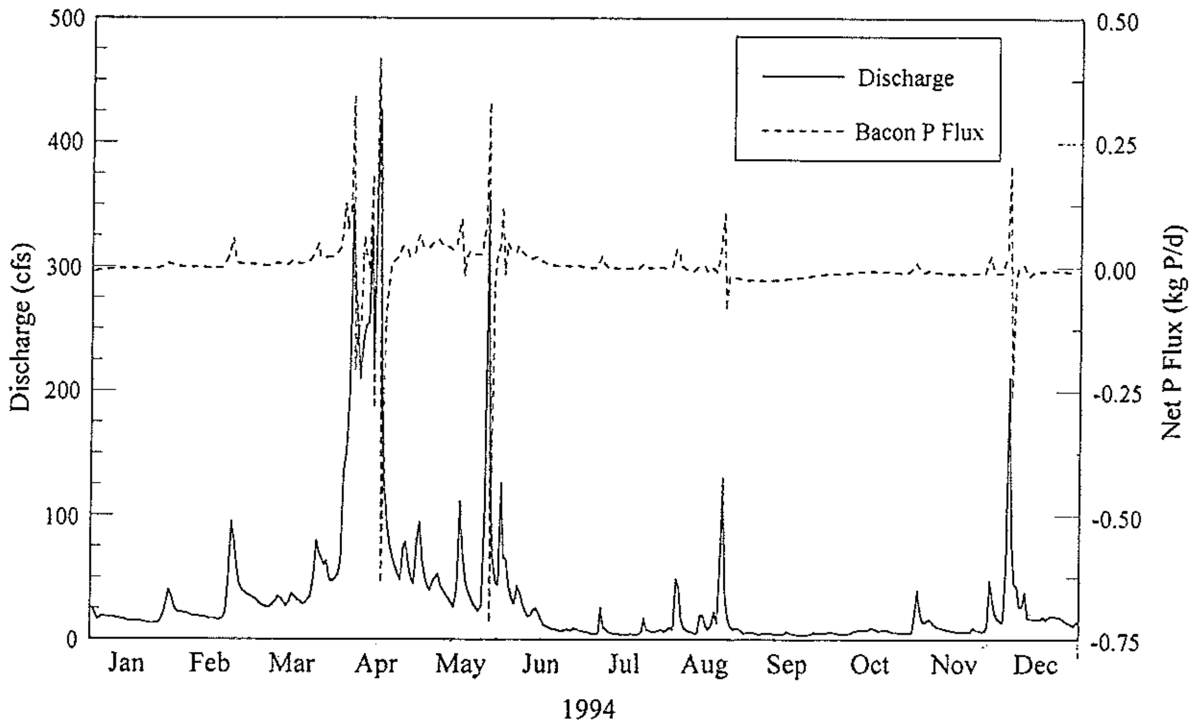


Figure 3.50 Measured hydrograph for 1994 and the calculated net P flux from the DSPM output for the Bacon Dr. site.

was negative (-0.3 kg P), however these values were not statistically different from zero for either reach.

3.7 LANDSCAPE STUDIES

The total stream surface area for the LaPlatte River to the mouth of the river in Shelburne Bay was estimated to be about 510,000 m^2. This area was fairly evenly distributed among stream orders ranging from 16% for first order streams to 27% for the single fifth order mainstream section. The first order streams comprise 156 separate stream sections, while the third order stream comprised only 8. The studied Spear St. and Bacon Dr. reaches were considered to be 4th and 5th order, respectively.

Combining the linear stream data with the digital elevation data for the LaPlatte River Basin allowed the average grade of each stream section to be calculated. The mean % grade (rise over run) for the stream orders was 3.2, 2.4, 0.75, 0.35, and 0.38 %, respectively (1st to 5th order). This suggests that in general, the character of the stream bottom probably varied greatly with stream order. Thus, extrapolation of results from the Spear and Bacon sites to other portions of the river to estimate whole river P stocks can only be done in a speculative manner (see Section 4.3).

DISCUSSION

4.1 OVERVIEW

The purpose of the LaPlatte River study described in this report was to support informed management of Lake Champlain Basin phosphorus sources through the provision of basic information on the P dynamics of basin streams. Concern about stream nutrient dynamics is related principally to nutrient impact on the water quality of Lake Champlain, rather than on the condition of the tributaries themselves. Hence, the fundamental question requiring attention was, do in-stream processes influence the total amount of P transported downstream (i.e., do streams retain P), the timing of P delivery to the Lake, or the bioavailability of transported P?

Streams are both complex and dynamic systems. In addition to the dominant force of downstream flow, there are numerous biotic and abiotic processes that influence P cycling. Sediments may adsorb or desorb P, macrophytes and periphyton growing on rocks (epilithon), plants (epiphytes) or any benthic substrate may take up P from the water to support their growth, or release it during senescence, and terrestrially-derived detritus may be involved in either P withdrawal from the water to support microbial growth or in P release as tissues are mineralized. All of these processes are influenced by P concentrations in the water, by temperature, and by water velocity. In addition, macrophyte and periphyton growth, and thus P demand, are influenced by light availability, and hence by the terrestrial canopy alongside the stream. Because all of these variables change with season and with place in a stream, it is not surprising that no simple formula will describe P cycling in all Basin streams at all times of year. In fact, the findings of our study suggest that both season and stream segment type are critically important in determining how P is processed. We also observed that the various processes interact: for example, epilithon matrices scavenge suspended particles from the water so that sediment retention is increased, and macrophytes "mine" P from sediments in summer, but then contribute to sediment P in the fall, as plant detritus is buried in sediments.

While it is not possible for this small, short-term project to provide a complete picture of a stream's P dynamics, we have been able to identify particularly important processes and P reservoirs in the LaPlatte River. These processes and stocks are discussed in Section 4.2. In addition, we have produced a dynamic model of stream P cycling that can be used by researchers and managers to investigate the behavior of small streams under different flow regimes and at different P concentrations. The results and limitations of this model are discussed in Section 4.3.

4.2 INTERPRETATION OF SPECIFIC COMPARTMENT RESULTS

4.2.1 Water

Both TP and SRP concentrations during our project (means of 90 and 40 μg P/L, respectively) were considerably lower than recorded during the ten-year water quality monitoring study on the LaPlatte River (Meals 1990), but were considerably higher than those reported in many other studies of phosphorus dynamics in lotic systems, which have tended to focus on forested upland or headwater streams (Elwood et al. 1981, Newbold et al. 1983, Mulholland et al. 1985, Graham 1988, Corning et al. 1989, Paul and Duthie 1989, Munn and Meyer 1990, Paul et al. 1991, Mulholland and Rosemond 1992, Rosemond 1994, Martí et al. 1994). The higher concentrations during summer in the LaPlatte River is a pattern that has been observed in other studies (Klotz 1991, Mulholland 1992, Rosemond 1994) and could be related to lower discharge at that time of the year and/or biotic factors. The variable amount of SRP in the LaPlatte that represented bioavailable phosphorus (BAP) is consistent with findings of others that have shown the percentage to generally vary from 10 to greater than 100 % of dissolved reactive P (Böstrom et al. 1988).

The phosphorus stock contained in the water compartment typically represented less than 1% of the total P mass within a reach. Water P stocks tended to be greater at Bacon Dr. due to the higher water volume present in the reach, rather than to consistent differences between sites with respect to water P concentrations. While strong seasonal differences in P concentration related to flow variations have been observed in the LaPlatte River in the past (Meals 1990), such seasonal patterns were not consistently observed during this study, probably because stock assessments tended to occur in low flow periods (see Figure 2.4). Seasonal patterns in P concentrations and stocks were, therefore, muted and did not reflect typical seasonal variability.

Despite comprising a very small stock, the low P concentrations in water may still strongly influence stream P dynamics. Mulholland et al. (1990), for example, found that biologically controlled P uptake was dominant in a Tennessee stream at SRP concentrations below 5 µg/L, but that physical/chemical sorption took over at higher SRP levels. In an Australian stream, Hart et al. (1992) found that P uptake rate per unit length of stream increased with increasing P concentrations in water.

Although water did not represent a major stock of in-stream P, water flow was clearly the dominant flux of P into and out of the study reaches, at least at low flows. The P fluxes of 0.8 to 3.9 kg/day in water far exceeded the <0.02 kg/day measured for detritus in transport, even though the water P fluxes measured at the relatively low flows were well below the annual average of nearly 40 kg/day (VT DEC and NYS DEC 1994). Phosphorus concentrations varied within a narrow range over the stock assessments; water flow was the primary determinant of P flux through the system.

No significant differences in phosphorus concentration were observed between upper and lower ends of either reach at any sampling time over the study. This suggests that the 150 m reach length was too short a distance or allowed for too short a residence time for processes controlling P uptake, release, or cycling among the other compartments to have an observable net effect on P concentrations in water under the conditions of the stock assessments. Based on the discharge during the stock assessments and on the net plume velocities recorded during the attenuation experiments, the 150 m stream reach represented a time of travel through the reach, or a water "contact time," on the order of 15 - 50 minutes. In a very general sense, this observation puts a lower limit on rates of P uptake/retention processes and on travel distance necessary to exert a measurable influence on P levels in water. That is, any processes resulting in measurable net loss (or net gain) of P from or to the water column probably take longer than 50 minutes. It should be noted that the sensitivity of the routine water TP analysis for stock assessments in this study was $\pm$0.01 mg/L. It is possible that greater analytical sensitivity, e.g. $\pm$ 0.001 mg/L, might have revealed a difference. Even a change of 0.001 mg/L P in 150 m could be significant at the scale of an entire river system.

Phosphorus measured in water represents the integration of P entering the stream reach from land or upstream loading and net release and/or leakage (spiralling) of P from in-stream processes. It is worth noting that, with the exception of the August 1994 stock assessment, water P concentrations and stocks appear to have followed a decreasing trend in both reaches (e.g., Figures 3.1 and 3.2) over the two years of this study. While this may be a coincidence resulting from stock assessments biased to low flows, this observation is consistent with a generally decreasing trend in P concentrations in the LaPlatte River since the late 1980s. Annual average TP levels in 1989, for example, were on the order of 0.7 - 0.8 mg/L compared to the 0.03 - 0.14 mg/L observed in this study. Other recent TP measurements (0.1 - 0.3 mg/L), taken predominantly during high flows in the LaPlatte River, have tended to confirm the lower P levels of recent times (Braun and Windhausen 1995). The upgrading of the Hinesburg wastewater treatment plant to P-removal in 1992 certainly caused a step-reduction in P inputs to the river, but continued declines in P concentrations in water may suggest a flushing of stored P from the river system, perhaps in response to diminishing supply of P stored somewhere in the system, e.g. in sediments. Release of P historically adsorbed in river sediments could be expected to be slow, as indicated by our laboratory adsorption/desorption experiments where only a small fraction of recently-sorbed P was released to filtered river water. The apparent decrease in sediment TP at both study reaches from Summer 1993 to Spring 1995 and laboratory evidence that LaPlatte River sediments are not close to saturation with respect to P are consistent with this speculation. It is, of course, also possible that the supply of P from the watershed , i.e. nonpoint source load, has been reduced leading to reductions in water P concentrations.

While both possibilities are highly speculative, a decreasing trend in P concentrations suggests that the system may not be in equilibrium, particularly with respect to sediments. P stored in sediments enriched from past high P loading to the river, for example, may be coming out into now lower-P water, but with sediment stocks being slowly depleted. This may have important implications for interpreting data from other compartments. If there was a net flux of accumulated P from sediments to water during this study, potential P uptake rates by sediments and/or rooted macrophytes may have been significantly underestimated.

4.2.2 Sediment

Defining the boundaries of the sediment compartment is somewhat arbitrary because the boundaries are ever changing and are dependent on the hydrologic regime at any given time. At low flow there may be a very shallow depth of interaction into the sediments (mm's or less), whereas at high flows this depth of interaction may be great (in excess of cm's). The wetted perimeter is also changing with changes in flow. As flow increases, the area of sediment in contact with water increases. Therefore it was necessary to set specific boundaries for the sediment compartment. These limits resulted in only sampling in-stream sediments, analyzing only sediment finer than 2 mm, and at Bacon Dr. analyzing sediments to a depth of 5 cm. Because the Spear St. sampling consisted of grab sampling interstitial material, the 5 cm depth limit was not exceeded. When TP levels were extrapolated to an areal amount (mg TP/m^2) the > 2 mm fraction was included in the calculations. All TP concentration data excludes the > 2 mm sediment fraction unless otherwise noted.

In this study two sediment extractions were used: NaOH and HCl. It should be emphasized that all extraction sequences attempt to provide discrimination on the basis of specific chemical properties (Hieltjes and Lijklema 1980, Williams et al. 1967). In actuality this results in an operational definition of chemical "fractions" of P which is a function of their solubility/reactivity in specific extractants rather then precisely defining the site, bonding mechanism or specific speciation of P within the sediment or soil. The NaOH extractable P has been widely used as indicative of "bioavailable" P whereas HCl-extractable P indicates total inorganic P (Böstrom, et al., 1988; Hosomi, et al. 1981; Young and DePinto, 1982). Undoubtedly, the distinction between these two extractions is not as precise as one would like. Nevertheless, such information is useful in making comparisons among different sediments.

Sediment TP concentrations at Bacon Dr. (0.55 to 0.70 mg P/g dry sediment) were comparable to those measured by Clapp (1995) for the Englesby Brook, VT. (0.41 to 0.62 mg P/ g dry sediment). As at Bacon Dr., Clapp (1995) also observed no differences in TP levels between sediment depth intervals (0-1, 1-5 cm). When the Bacon Dr. sediment samples were split into sand and silt+clay fractions and analyzed separately for TP, it was found that the silt+clay fraction had the higher concentration of TP (by 2 to 6 fold). This finding is consistent with others in the literature, for example, Stone and Murdroch (1989) observed that the majority of P_2O_5 in the sediments of the Big Creek and Big Otter Creek of southwestern Ontario was found in the <13 um fraction (medium silt and finer).

The extraction results for the Bacon Dr. site showed an average NaOH-P concentration of 0.07 mg P/g dry sediment and an average HCl-P concentration of 0.32 mg P/g dry sediment, representing 14% and 62% of the sediment TP, respectively. In comparison with other river and lake sediment studies, the NaOH-P concentrations at Bacon Dr. are low. Rosensteel (1991) found concentrations in the NaOH-P of 0.47 mg P/g and TP of 1.07 mg P/g in two Pennsylvania rivers. In another Pennsylvania watershed, Pionke and Kunishi (1992) found sediment NaOH-P and TP concentrations almost as high: 0.35 mg P/g and 0.90 mg P/g respectively. A study of St. Albans Bay, (Lake Champlain) sediments by Ackerly (1983) measured NaOH-P concentrations as high as 1.78 mg P/g and TP concentrations as high as 3.26 mg P/g. A review of the literature revealed no studies of HCl-P in river sediments. However, Ackerly (1983) found HCl-P concentrations in St. Albans Bay as high as 1.04 mg P/g. It is important to note that while in lake sediments NaOH-P is the predominant P fraction, HCl-P was more significant in the Laplatte River sediments. It is also important to note that when NaOH-P concentrations are extrapolated to an areal scale, there are at least 2520 mg, and up to 4480 mg of NaOH-P per square meter of in-stream sediments. This fraction is generally considered to be roughly equivalent to the biologically available P (Böstrom et al. 1988, Hosomi et al. 1981, Young and DePinto, 1982).

Sediment TP concentrations at the Spear St. site ranged from 0.35 to 0.50 mg P/g dry sediment, with no significant seasonal differences. When the > 2 mm sediment fraction was added in , the TP concentrations of 0.007 to 0.13 mg P/g dry sediment are comparable to those measured by Klotz (1991) in Hoxie Gorge Creek, NY. Klotz (1991) analyzed sediments from a reach that was described as cobbles with interspersed coarse sediments and found a mean TP concentration for monthly samplings in 1988 of 0.043 mg P/g. The TP concentrations for the two different sediment size fractions analyzed at Spear St. showed similar concentrations as the same sediment size fractions analyzed at the Bacon Dr. site. The range in the silt+clay and sand fractions were 1.5 to 2.8 mg P/g dry sediment and 0.25 to 0.5 mg P/g dry sediment respectively. The NaOH-P and HCl-P concentrations for the Spear St. interstitial sediments were very similar to the concentrations in the Bacon Dr. sediments. The NaOH-P and HCl-P at Spear St. were 16% and 62% of the TP, respectively. The estimate of BAP (NaOH-P) in the sediments at the Spear St. reach is therefore at least 240 mg per square meter for a 5 cm depth interval and a 28% coverage of interstitial material.

Although there are some similarities, sediments at Bacon Dr. and Spear St. differed in several ways. Grain size distributions showed Bacon Dr. sediments as predominantly sands whereas the Spear St. site interstitial material was mostly gravels. The TP concentration levels at the Bacon Dr. site were two times those at the Spear St. site. When TP concentrations are extrapolated to mass of TP per area per depth of 5 cm it was found that Bacon Dr. sediments contain ten times as much TP as those at Spear St.(> 2 mm sediment included for both sites). Klotz (1991) found similar differences between a predominately sandy site and a site with cobbles and interspersed coarse material: the finer grained site contained 5 times as much TP as the coarse grained site. It appears then, that the amount or percent of fine grained sediment present in any one sample or reach controls the overall TP concentration within the sediments in the sample or reach. However, no significant correlation was found between TP concentration and sediment grain size (either %sand or %silt+clay) for the Bacon Dr. site. The Spear St. site did show a very slight correlation between %sand and TP in mg TP/g dry sediment with r^2= 0.4 n= 6 (Figure 4.1). However, this correlation is not significant to a 95% confidence interval.

Both study sites showed a pattern, though not statistically significant, in the TP concentration of the silt + clay fraction (Figure 4.2). In general, the concentration of TP in the silt+clay fraction increased in the fall, decreased slightly in the winter, and continued to decrease into the summer and then increased in the fall. This pattern or trend may reflect plant uptake of TP from the sediments during the growing season and then a release of TP to the sediments during plant senescence. In a study of Lake Memphremagog, (Quebec-VT) Carignan (1985) found that sediment pore water reactive P decreased around the root zones during summer months due to plant growth and increased in the fall and spring due to partial root decomposition. Further evidence for plant use of sediment P was obtained by Chambers et al. (1989) for a study of the South Saskatchewan River, Canada, macrophytes were planted in buckets containing sediment with high concentrations of P and in buckets containing low concentrations of P. Both types of P enriched sediment buckets were placed in flowing river water with high concentrations of P and in flowing river water with low concentrations of P. Chambers et al. 1989 observed that of the plants placed in low P concentration water, the ones in the high P concentration sediments had a greater biomass and higher nutrient concentrations (1.67 to 0.29 g dry /pail and 3.77 to 1.82 mg P/g dry wt. respectively). It was also observed that of the plants placed in water with high P concentration, the plants in high P concentration sediments again had the higher biomass and nutrient concentrations (1.83 vs. 0.38 g dry / pail and 3.88 vs. 2.50 mg P/g dry wt., respectively).

The storm data for both sites showed that there was sediment movement and change in TP concentration associated with flow increases. As Verhoff et al.(1980) showed in a study regarding P transport in rivers, TP levels increase with increasing flow because suspended

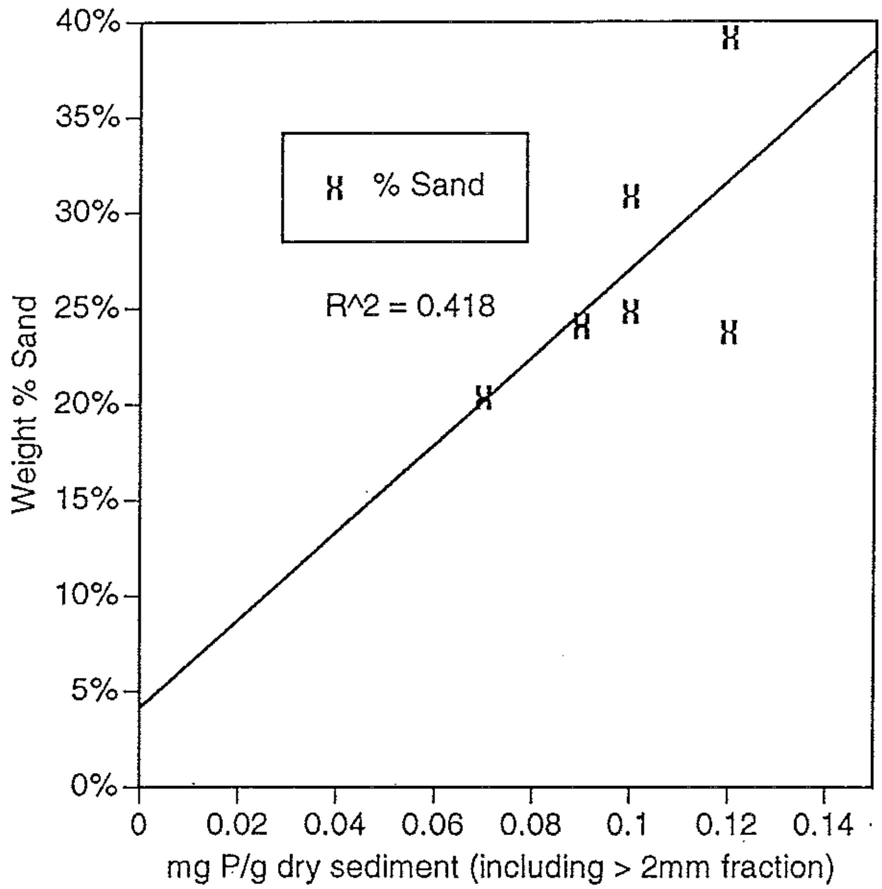


Figure 4.1 Spear St. correlation of percent sand by weight and TP concentration including the greater than 2 mm fraction.

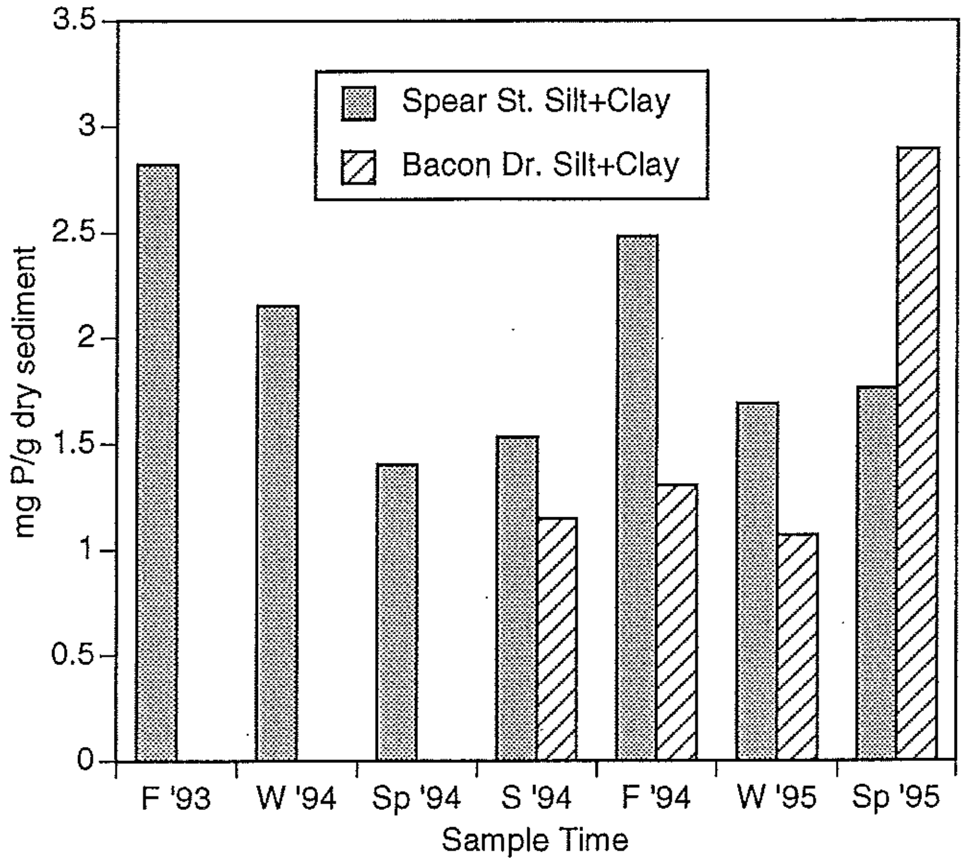


Figure 4.2 Spear St. and Bacon Dr. sediment TP concentration in the silt+clay fraction as mg TP/g dry weight versus time. There is no data for Bacon Dr. for Fall 1993, Winter 1994, and Spring 1994.

sediment is added through channel scour. Verhoff concluded that resuspension at high flow followed by deposition is the major mechanism responsible for moving TP a finite distance through a river system. In general, the results from scour chains placed at Bacon Dr. and grain size analysis for the pre- and post-storm sediment samples at both sites showed sediment movement and a decrease in the sand and silt+clay fractions, suggesting a down stream movement of high P content sediments.

It is clear that the sediment compartment represents the major repository of P within either reach at all seasons. Sediment heterogeneity and variable compartment boundaries as a function of hydrodynamic conditions make it difficult, if not impossible to ascertain changes in the sediment stock by random sampling methodologies. The within reach variability of sediment TP appears to be far greater than the average change due to input or export. As suggested by numerous studies (Verhoff 1978, Pionke and Kunishi 1992), the transport of P both through a reach and from within a reach will be dominated by the physical transport of sediment as both suspended material and as bedload. Such transport is extremely dependent upon relatively short term fluctuations in the hydrology caused by flow response to specific storm events or seasonal patterns, such as snow melt, spring runoff, etc. In these cases, material removed from a reach is undoubtedly replaced on a long term basis by material moving into the reach. Otherwise there would be rapid net erosion by the stream.

Thus more so than the other compartments, the importance of sediments to P transport and transformation is perhaps best assessed by investigating specific flux paths rather then stock variables.

Sediment adsorption-desorption of phosphorus in aquatic systems has been investigated as a nutrient source, but the major emphasis has been on lacustrine rather than fluvial sediments (Böstrom et al. 1982). Adsorption-desorption properties of sediments can be expected to vary significantly from one sediment reservoir to another making generalizations difficult. There is, however, a consensus that fine grained materials such as iron oxides and clays are more effective at adsorbing P than are larger particles, although it appears that the dominant controls are particle geochemistry and mineralogy not particle size (Stone and Murdoch 1989, Fox 1993). Thus, it is to be expected that adsorption-desorption characteristics will vary with sediment composition, particle size and the geochemical characteristics (e.g. pH, Eh) of the adjacent water, all of which are strongly impacted by *in situ* biological and hydrologic conditions.

Bacon Dr. sediments exhibited a well defined adsorption pattern that can be characterized by either a Langmuir isotherm or a Freundlich isotherm (see Section 3.3.7). The Langmuir isotherm,which was employed in model development, provides a quantitative measure of the maximum adsorption capacity as well as the affinity constant, essentially an equilibrium constant relating the solution equilibrium concentration to adsorption (Holtan et al. 1988, McCallister and Logan 1978, Stumm and Morgan 1988). The maximum capacity of the Bacon Dr. sediments thus calculated was approximately 0.25 mg P/gm sediment. McCallister and Logan (1978) in their study of bottom sediments from the Maumee River basin, Ohio, determined maximum adsorptive capacities ranging from 0.222 mg P/gm for sandy sediments similar to those sampled in this study to 4.870 mg/gm for very clay and silt rich sediment. The affinity constant, or adsorption energy as defined by McCallister and Logan (1978) was 1.09 mg/L for Bacon Dr. sediments, and ranged from 0.65 mg/L to 1.47 mg/L for bottom sediments from the Maumee River. Sandy sediments, most comparable to the Bacon Dr. material had an affinity constant of 1.00 mg/L. Thus the results of their study and this investigation are similar. In comparison to a maximum adsorptive capacity of 0.25 mg/g, the average total P content of the Bacon Dr. sediments was approximately 0.6 mg/g suggesting that, even at maximum saturation, sorbed P represents less than 50% of the total P. However, it also appears as if the Bacon Dr. sediments have a large unutilized sorptive capacity. This is further corroborated by the fact that NaOH extractable P (Section 3.2.3), generally considered to be held on OH-exchangable surface sites on Fe-Al sesquioxides and clays, represented approximately 15% of the total P. Results of the adsorption study clearly indicate the potential for sediments to moderate or lower the aquatic concentrations of P. Rate studies indicate that the adsorption takes place rapidly, with final values being reached in approximately 6 hours, a time framework short enough to be effective with an extended fluvial system but not within a 150 meter reach. Note that the travel time of the P plume during the summer attenuation study was 23 hours over just a 3 km reach.

When sediments upon which P had been sorbed were placed in dilute aqueous solution the amount of P released was related to the amount initially adsorbed, but only a small fraction (usually less than 10%) of the recently sorbed P was released over 24 hours. This suggests a nonreversible, or kinetically slow (at least within the 8 to 24 hour time framework of the experiment) mechanism. It is also possible the some component of the uptake may not be due to physicochemical adsorption, but rather due to uptake by bacteria or epipelic periphyton present in the sediment, in which case it would not be reversible.

When extrapolating the results of both the adsorption and desorption studies to the natural environment it is necessary to exercise extreme caution, because it is highly unlikely that the 30 ml sediment/solution slurries agitated for 24 hours in the laboratory simulate *in situ* conditions. In the natural environment the effectiveness of sediment-water interactions will be highly variable, dependent upon factors such as resuspension and hyporheic flow. In fact Hill (1982) states that P sorption by undisturbed sediments was considerably slower than rates observed in agitated laboratory samples. Nevertheless, it seems clear that adsorption is an important process in reducing the P content in natural fluvial waters. The role of P desorption from sediments is far more problematic.

4.2.3 Epilithon

Periphyton contribute in varying degrees to the uptake, storage and cycling of phosphorus in lotic systems. In heavily shaded and/or grazed streams, the contribution of periphyton to P dynamics can be much less than that of CPOM and its associated microorganisms (Elwood et al. 1981, Newbold et al. 1983, Mulholland et al. 1985). In contrast, when periphyton dominate a stream due to sufficient light and/or minimal grazing, they can play a major role in the active uptake, storage and cycling of phosphorus (Mulholland et al. 1995, Steinman et al. 1995).

The epilithic periphyton (epilithon) biomass quantified in this study (mean of 20 - 40 g AFDM/m ^{2} of rock substrate for the slow and fast flow sites, respectively) was markedly higher than reported for most other studies. The elevated phosphorus levels in the LaPlatte river and the openness of the sites are likely factors contributing to the high epilithon biomass in this river. Generally, epilithon biomass of lotic systems ranges from 5 to 15 g AFDM/m ^{2} (Nelson et al. 1969, Corning et al. 1989, Paul and Duthie 1989, Rosemond 1994), with lower values (< 2 g AFDM/m ^{2}) reported from heavily shaded streams (Newbold et al. 1983, Mulholland et al. 1985). In contrast, Graham (1988) reported epilithon biomass levels of up to 40 g AFDM/m ^{2} in a New Zealand river, values comparable to the biomass measured in the LaPlatte river. Interestingly, in that same study Graham (1988) reported a high ash content (mean: 78% of dry weight) due to entrapped fines (silts and clays) associated with the epilithon, which is comparable to that measured in the LaPlatte epilithon. Perhaps the high amount of entrapped silts and clays are a significant nutrient source that stimulates epilithon production. Burkholder (1992) has shown suspended clays to significantly adsorb phosphate and also stimulate phosphate uptake by phytoplankton in a turbid reservoir of the southeastern United States.

In a countervailing fashion, increased ash elevated the epilithon mass per unit area but reduced the % P, since the silts and clays in the LaPlatte river have a lower P concentration than does biomass (see Section 3.1.2.). Since fines deposit onto the epilithon matrix independently of flow rate (Graham 1990), whereas algal production is stimulated at higher flow rates (Horner and Welch 1981, Wheeler 1988, Raven 1992), it is consistent that the epilithon at the slower flowing site (Bacon Dr.) had a higher proportion of ash than at the faster flowing site (Spear St.). It is possible that these trapped fines may be lowering the food quality of the epilithon to herbivores, potentially altering trophic structure and P cycling (Graham 1988, 1990, Davies-Colley et al. 1992). Microscopic observations suggest that the relatively high epilithon stock during winter seems to be a combination of over-wintering *Cladophora* akinetes and associated diatoms, macroinvertebrates and entrapped fines. High periphyton stocks during winter (measured as chlorophyll *a*) were also reported by Delong and Brusven (1992) in a eutrophic river in an Idaho agricultural basin with similar total and SRP concentrations to the LaPlatte River.

Estimated fluxes in the LaPlatte were calculated with bioavailable P instead of the two to twenty times higher SRP concentrations in this river. The use of BAP instead of SRP for estimating P flux in the epilithon seems justified since calculations of approximate daily production from the measured P flux and percent P of the epilithon were comparable to average daily production rates calculated from mass differences. Production, based on dry weight changes, was calculated for three different intervals: two during June 1995 (the four-day period around the release of the phosphate pulse and the 28-day clay saucer experiment), and one during August 1994 (the seven-day interval that encompassed the storm). Flux, estimated with $^{33}P\text{-}PO_4$ uptake, was determined in June 1995 within 24 to

48 h of the end of the saucer experiment, and also in August 1994 just after the summer storm. The flux-based production rates (corrected for the killed controls) were 2 $g/m^2/d$ in June 1995 and 20 $g/m^2/d$ in August, 1994, compared to mass-difference production rates of 3 and 16 $g/m^2/d$ in June and August , respectively.

What one assumes is available P is important in comparing fluxes from different studies, since the uptake rate constant for orthophosphate (estimated with ^{33}P- or ^{32}P-PO_4) times the amount of available P (assumed to be primarily orthophosphate) is a commonly used method for estimating P flux. The majority of studies of periphyton-phosphorus dynamics (Elwood et al. 1981, Newbold et al. 1983, Mulholland et al. 1985, Corning et al. 1989, Paul and Duthie 1989, Paul et al. 1991, Steinman et al. 1991, Mulholland et al. 1995, Steinman et al. 1995) have used this approach and have assumed SRP is all biologically available (but see Section 3.2.2 and Figure 3.27). The maximum fluxes reported in these studies have ranged from less than 1 μg P/ m^2/ min in streams with heavy shading, low biomass and/or low SRP levels, up to about 10 μg P/ m^2/ min in periphyton-dominated streams. Munn and Meyer (1990) measured SRP uptake rates by a nonradioactive P method (Stream Solute Workshop 1990) in two forested headwater streams and reported a maximum uptake of about 20 μg P/ m^2/ min.

The estimated fluxes in the LaPlatte River during the fall and spring were comparable to the levels reported in these other studies. It is important to keep in mind that if we had used SRP as an estimate of available P, as the majority of the other studies have done, our calculated fluxes would have been two to ten times higher. The higher areal uptake rate estimated for the slow flowing site (Bacon Dr.) during fall was due to the higher level of BAP measured at that site, whereas the higher specific uptake rate at the fast flow site

(Spear St.) was due to the considerably higher biomass present at that site. Thus, it seems likely that P flux into the epilithon in the LaPlatte is appreciably higher than reported for most other stream systems. P flux in the LaPlatte appears to be more similar to that of the non-light limited, calcareous stream, with comparable epilithon production, that was studied by Martí et al. (1994). In that study, SRP uptake was estimated by the same method used by Munn and Meyer (1988), and found to range from 50 to 160 $\mu g\ P/m^2/min$, which is comparable to estimated uptake rates for the LaPlatte, if SRP concentration is used as an estimate of available P instead of BAP.

A significant portion (20 to 43 %) of the total uptake measured in this study was due to passive uptake (adsorption), as measured by killed controls. Lock (1979) also reported significant passive uptake of ^{32}P phosphorus (25 to 50 % of the total) by river epilithon, which he attributed to the "polysaccharide-like" matrix functioning as an adsorption agent. Therefore, given the mucopolysaccharide nature of the epilithon matrix and the high percentage of entrapped fines in the LaPlatte epilithon, it seems likely that the appreciable P uptake by the killed controls represents an innate property of epilithon communities which significantly contributes to the phosphorus dynamics of these biofilms.

The much greater uptake rates in August, measured within 2 days of the peak discharge from the summer storm, probably reflect storm-related enhancement of epilithon growth. Stevenson (1990) noted positive effects, including increased abundances, on benthic algae following a storm. Part of the doubling of epilithon mass associated with the August storm may be due to an increased percentage of ash (from about 70 to 86 % of the dry weight), which would have likely enhanced uptake due to adsorption (Burkholder 1992). However, the amount of increase in ash content is too little to fully account for the markedly higher P uptake rates.

Total phosphorus concentration in the LaPlatte, before and after the storm, increased from about 140 to 190 μg P/L, which is consistent with reported increases in nutrient concentrations after subscouring spates, especially in agricultural basins (Humphrey and Stevenson 1992). Bothwell (1988, 1989) has shown that production in thin periphyton biofilms is primarily controlled by cellular growth kinetics which saturate at low P concentrations (< 1 μg P/L), whereas areal productivity of thicker biofilms does not saturate until P concentrations reach about 30 μg P/L and appears to be controlled by physical diffusion of P into the periphyton matrix. Stevenson and Glover (1993) have shown that mass transport from the water column through a periphyton mat decreased with algal density and increased with flow rate. Thus it seems that the measured increase in total phosphorus concentration and high BAP levels after the storm, coupled with increased flow rates and turbulence, are likely responsible for the higher P uptake rates, since these conditions would enhance diffusion. The appreciable enhancement of P uptake in the spring (phosphate additions of similar magnitude to the August BAP concentration produced rates comparable to those measured after the August storm) is consistent with the theory of mass transport limitation in these thick epilithon communities.

However, the nutrient-diffusing substrate experiment suggests that neither phosphorus nor nitrogen limit epilithon growth in this system. It is possible that the clay substrates used in this experiment adsorbed sufficient phosphate from the water to minimize any treatment effects relative to the control over the duration of the experiment. A more likely cause relates to the fact that the epilithon mass that accumulated on these artificial substrates over the 28 day experiment was less than half the mass on adjacent natural substrates (mean of about 76 as compared to about 190 g/m^2). As such, the epilithon biofilms were relatively thin and the dominant mechanism controlling biomass accumulation may have been cellular growth kinetics that saturate at a much lower phosphate level compared to whole-mat growth kinetics (Bothwell 1988, 1989).

In conclusion, it appears that the epilithon in the LaPlatte River are more productive and contribute substantially more to phosphorus dynamics than reported for many other river systems. Furthermore, it would seem that the periphyton in general (epilithon, epiphytes etc.) are acting as a P sink (at least during the growing season from mid-spring to mid-fall) to the extent that from 1 to 10% of the P flux in the water may be retained in the stream. However, over an annual cycle it seems likely that the majority of this retention would be transported downstream as part of the bedload and suspended load. The use of BAP instead of SRP for estimating P flux in the epilithon seems appropriate given the acceptable agreement between production estimated by both mass difference and P uptake. The very high epilithon ash content suggests that there is an interaction between epilithon and sediment transport that warrants additional investigation. These entrapped silts and clays may be having multiple influences ranging from nutrient effects to alteration of trophic dynamics to possible attenuation of light energy and its effect on production.

4.2.4 Plants and Epiphytes

Macrophytes in the LaPlatte River are very patchily distributed. Rooted plants are sparse in riffle reaches, particularly where the bottom is cobbly, but fairly common in reaches with soft bottoms and slow flow. Current velocity influences plant biomass both through its direct impact on plant sloughing and uprooting, and its impact on sediment composition. Soft bottom sediments allow for better plant rooting, and a richer nutrient supply (Chambers et al. 1991). Research on stream macrophytes in western Canada has shown that plant abundance generally decreases with increasing velocity over the range 0.01-1.0 m/s; at current speeds in excess of 1.0 m/s, aquatic macrophytes are very rare (Chambers et al. 1991). Our study highlighted major differences in plant abundance at the two study reaches: P storage in macrophytes was two orders of magnitude greater at the slow-flowing soft-bottomed Bacon Dr. site (summer flow velocities generally between 0.05 and 0.15

m/s) than at the more riffly Spear St. site (summer flow velocities generally between 0.09 and 0.25 m/s, but exceeding 1 m/s during spates). At Spear St., plants were confined to quiet back pools, where flow velocities were reduced and pockets of sediment had accumulated. Elsewhere in the stream, sediment substrate for rooting was minimal. Even at Bacon Dr., plant distribution was influenced by flow velocity; plants were sparse along the major flow path of the water, and reached maximum densities in deep pools away from the main flow path.

At Bacon Dr., macrophytes and their epiphyte associates stored about 1 gram of P per m^2 of stream bottom during midsummer (Tables 3.9 and 3.10). They were, therefore, the major P store in this stream reach, apart from sediments. In contrast, macrophytes and epiphytes at the Spear St. site accounted for no more than 0.02 g P/m^2 . In both reaches, macrophytes and epiphytes contained roughly equal amounts of P (based on 1994 data).

Macrophyte growth in the LaPlatte River, as elsewhere in temperate regions, is highly seasonal. While some species, like *Elodea* overwinter under ice in small numbers, most macrophytes die back in autumn and remain dormant until late spring. We occasionally collected an *Elodea* sprig during winter samplings, but our estimates of winter biomass were always very low (<0.1 g/m2), suggesting that P storage in the macrophyte and epiphyte compartments during this season is negligible (<001 g/m^2). Macrophytes in the LaPlatte germinate in May and June. Hence our spring sampling of 1995, which took place in April, showed no more macrophyte P storage in the two reaches than in winter, while the May sampling of 1994 indicated that the plants were growing and incorporating P. P storage at Spear St. in May was just one third what it would be in August, however. At Bacon Dr., the seasonal difference was much more dramatic: P storage increased 70 fold between May and August. Later, during September and October, plant biomass, and hence the P storage capacity of the macrophyte compartment, declined as the plants senesced.

Macrophytes can obtain P from either sediments or the water. While there have been many studies assessing the relative importance of sediments and water as P sources for lacustrine plants, our study in flow-through microcosms was the first to examine source partitioning among riverine plants. In lakes, sediments generally provide most of the P incorporated into plants (Smith 1978, Carignan and Kalff 1980, Penhale and Thayer 1980, Twilley et al. 1977, Carignan 1982, Moeller et al. 1988). Lake sediments are rich in P, while lake waters tend to be depleted, so exploitation of the sediment source makes sense. There are a number of reasons to suspect that P source partitioning might be different in streams, however. Stream sediments generally are coarser and subjected to a higher rate of pore water flushing than are lake sediments, while P concentrations in stream water are generally greater than in lakes. Furthermore, water flow continually renews the water P source in streams. Reviewing the literature on P source partitioning in lakes, Carignan (1982) found that the ratio of water to sediment P uptake by plants increased substantially as the ratio of water to pore water SRP concentration increased. At a ratio of 1:1, water uptake predominated.

Our experiments in flow-through microcosms indicated that the macrophytes at Bacon Dr. take up substantial amounts of P from the water, from 0.03-0.11 mg P/g/day. Our estimates of plant P uptake from sediments are less reliable due to the lack of a good estimator of phosphate availability in sediments, and to the very low slope of the uptake curve for ^{32}P movement from sediments to plants. However, it appears that in the LaPlatte River, uptake of P from sediments is generally lower than uptake from the water. This conclusion is compatible with the predictions of Carignan's model; SRP concentrations in the pore waters of the sediments in our microcosms were similar or less than the concentrations in the overlying stream waters.

The above findings have implications for P spiraling in streams. When macrophytes obtain P from sediments, they are a P source for the stream. Live plants release very little P into the water around them (Granéli and Solander 1988), but dead plant material often undergoes decay above the sediment surface. When, on the other hand, plants obtain much of their P from the water, as the macrophytes in the LaPlatte appear to do, they are a P sink, although a seasonal one.

Epiphytes in the LaPlatte River, which get all of their P from the water, had greater specific phosphate uptake rates (rates of P incorporated per g per day) than macrophytes, and a similar biomass. Hence, epiphytes appear to play at least as great, if not a greater, role than macrophytes in removing phosphate from water flowing down the LaPlatte River.

Extrapolation of the microcosm results to Bacon Dr. (adjusting for the biomass present in the stream) suggests that in August 1994, macrophytes and epiphytes on the stream bottom removed between 30-40 mg of P per m^2 per day. By mid-September, this flux had diminished to about 12 mg P/$m^{2/}$day. The August flux of P to macrophytes and epiphytes was too small (0.050 - 0.08 kg/day for all of the Bacon Dr. reach) to seriously impact the downstream transport of P in the LaPlatte (total P transport was 2.6 kg/day; Table 3.3). The flux, however, was great enough to remove 6 - 10% of the BAP moving downstream. Were macrophytes and epiphytes the only P removal agents in the LaPlatte, the spiral length for BAP in macrophyte-inhabited reaches would be on the order of 2000 m.

Additions of phosphate to experimental microcosms greatly stimulated phosphate uptake by both macrophytes and epiphytes. This suggests that the phosphate permeases of neither group were saturated. Consequently, increases in phosphate concentration in the stream might stimulate increased biological uptake.

4.2.5 Detritus

Past studies of P dynamics in streams have shown detritus to be an important P store and the biofilms on detritus critically important P uptake sites. In a 13 year study of Bear Creek, NH, Meyer and Likens (1979) found that leaf litter contributed 23% of incoming P, and that 62% of P left the stream as fine particulate material produced by detritivores. Mulholland et al. (1985) used a radiotracer, $^{32}PO_4$, to examine seasonal changes in P dynamics in Walker Branch, TN. Phosphate spiral length (average distance of phosphate travel before uptake) in this heavily shaded stream was found to vary from 22 m in November, when leaf debris was abundant, to 97 m in August. In all seasons, a large proportion of the radiotracer removed from stream water was incorporated into CPOM (89% In fall, 26% in winter, 44% in spring and 48% in summer) or into benthic FPOM (fine particulate organic matter; 23-57%). By contrast, epilithon removed just 5-9% of the P.

The LaPlatte River differs from Bear Creek and Walker Branch in that it runs largely through agricultural land; only the upper 20% of the river's watershed is forested. While some trees are found along the stream's main stem, tall grasses are the principal riparian vegetation. Consequently, the stream does not receive much leaf litter from the surrounding landscape and its open canopy permits substantial periphyton and macrophyte growth on the stream bottom. Therefore, we anticipated that detritus would play a much lesser role in LaPlatte River P spiralling than it does in the forested streams which dominate the literature on stream P dynamics.

Because CPOM has been particularly important in P spiralling elsewhere, our sampling efforts emphasized quantification of the P associated with this detrital fraction (leaves, twigs, and the occasional dead macrophyte or invertebrate). As expected, we found about an order of magnitude less CPOM in the LaPlatte (per m^2) than is present in Walker Branch. However, this observation must be qualified by noting that while we picked up only that detritus which we could see on the sediment surface (>1 cm length), at Walker Branch, organic floc was pumped off the bottom and sieved to yield an estimate of CPOM (which was defined as organic material > 1 mm in size). Thus some of the organic material (and P) that we classified as "sediment" would be classified as CPOM by the Walker Branch (and other) investigators.

CPOM was found to be more abundant in the Bacon Dr. reach than in the Spear St. reach, probably because water flowed more slowly at the former site, and thus was more likely to deposit its detritus load. As anticipated, CPOM stocks were greatest in autumn, principally because of leaf fall at this time of year. At Bacon Dr., detrital mass declined during winter and spring, and reached a minimum in summer. This was the same pattern of detritus storage and loss observed at Walker Branch (Mulholland et al.1985). Because major summer high flow events did not occur in 1993 and 1994, the loss of detritus from the LaPlatte in summer was probably associated with enhanced decomposition rates at high temperatures. It also may have been buried in sediments.

Our radiotracer experiments indicated that the specific rate of phosphate uptake by CPOM (uptake per gram of material) was similar in magnitude to uptake by epilithon and epiphytes, and somewhat higher than uptake by macrophytes. Rate of uptake was influenced by substrate type. Uptake onto dead macrophytes (mean = 35 µg P/g/day) was three times as great as uptake onto tree leaves (11 µg P/g/day), and 100X as great as uptake onto the biofilms of twigs (0.02 µg P/g/day).

The specific phosphate uptake rates measured for leaf and macrophyte debris were comparable with those reported in the literature. For example, in Walker Branch, CPOM removed phosphate at rates ranging from 12 μg/g/day in summer to 41 μg/g/day in autumn (Mulholland et al. 1985). Nevertheless, the areal flux of phosphate to the stream bottom due to uptake onto CPOM was much lower in the LaPlatte (1.7 mg/m^2/day at Bacon Dr. in autumn) than it was in Walker Branch (ranging from a low of 1.9 mg/m^2/day in summer to a high of 23 mg/m^2/day in autumn) because the mass of detritus was lower. Because P uptake by CPOM was measured at Bacon Dr. in autumn during leaf fall, one might speculate that the daily contribution of detritus to P spiralling at this site is lower during most of the year.

Tree branches and logs were not included in our estimate of CPOM; their mass in the stream and their contribution to P cycling were assessed separately. For most samplings, wood mass in the stream reaches exceeded the mass of CPOM, often by many fold. The P content of wood was only slightly less than that of CPOM; hence much of the detrital P reserve in the stream reaches was associated with wood. However, wood was not a good substrate for biofilm communities active in phosphate uptake. The specific phosphate uptake rate onto wood was two orders of magnitude lower than that onto either tree leaves or dead macrophytes, and the flux of phosphate-P into wood on the stream bottom at Bacon Dr. was estimated to be less than 0.005 mg/m^2/day. This flux accounted for only about 0.5% of the total flux to detritus.

Detritus in suspension moves downstream with the water flow. When water samples are collected for particulate and dissolved P analysis, pieces of leaf or twig material generally are removed prior to filtration. Consequently, the amount of detrital P in water and its flux downstream are very rarely quantified. To remedy this methodological shortfall, we designed a trap to catch suspended detritus moving downstream. When data on the catch of this trap are combined with flow data, detrital P flux downstream can be estimated and added to estimates of dissolved and particulate P transport (Section 3.1.5).

The trap data revealed a relationship between the quantity of detritus in suspension and water velocity (Figure 3.20), but at the low flows of our study (< 0.8 m/s), the amounts moving downstream were small. Thus, for the LaPlatte River, collection of water samples (without estimation of detrital P) seems justified, except perhaps at high flows, when detritus might be lifted off the bottom. The trap should be further tested at sites in forested watersheds, where detritus is more likely to carry more of a stream's P load.

Decomposition studies using litter bags in the stream indicated that P release into the water from bottom detritus is generally low in the LaPlatte, just 0.06-1.2 $mg/m^2/day$ during Fall 1994, largely because the mass of material on the bottom is small. The data from Fall 1994 suggest that total decomposition of leaf material occurs over a period of about one year or more (238 d at Spear St., 526 d at Bacon), while aquatic plants decompose within a two month period. In reality, decomposition rates are probably faster in summer when temperatures are warmer. It is interesting to compare decomposition rates with detrital transport downstream. During our seasonal samplings, only 0.01-0.23 % of the CPOM in either of the reaches was present in suspension. If it is assumed that equal amounts of detritus are lifted off the stream bottom each day, transport of the measured benthic CPOM stocks downstream should require on the order of 400-10,000 days (1-27 yr). This suggests that much of the detritus in the LaPlatte River is decomposed within the stream channel, rather than in Lake Champlain, or, alternatively, that detritus flushing downstream occurs as a step function driven by the storm and snowmelt events that generate high flows.

While our study indicated that detritus normally plays only a minor role in the LaPlatte P cycle, extrapolation of our study results to other streams in Lake Champlain Basin must be done with great caution. Streams in forested watersheds on the NY side of the Basin probably contain much more leaf litter than the LaPlatte and also are expected to be more shaded (reducing the role of periphyton and macrophytes in P spiraling). In these streams, detritus might play a major role in P storage and cycling, as it does in Walker Branch.

4.2.6 Attenuation Experiments

In the attenuation experiments (which involved a 3 km reach considerably longer than those used for stock assessment), both the conservative dye and the soluble reactive P were transported downstream at net velocities well below observed current velocities and were spread out considerably in time and space from the initial instantaneous injection. Such "transient storage" has been widely observed in stream solute injection studies and is usually attributed to temporary trapping of flowing water in eddies, pools, or other hydraulically "dead zones" in the stream and to very short term exchange with the hyporheic zone (Bencala et al. 1984, Triska et al. 1989, Stream Solute Workshop 1990). In general, it is to be expected that actual travel time of any substance introduced to the streamflow will exceed the minimum convective travel time due to transient storage.

However, while the transport of both substances was altered by these purely hydrodynamic processes, phosphorus transport was further altered compared to the conservative dye tracer. In both seasons, the added P was delayed and spread out more than the dye and therefore transported downstream more slowly . Under both winter and summer conditions, a net, short-term, reversible P retention was observed over the 3 km stream reach. This short-term retention was greater in the summer (759 g P or 25 mg/m^2) compared to the winter (308 g or 10 mg/m^2), and persisted longer in the summer (7 hours) than in the winter (2.5 hours). The slower transport velocity in summer may explain part of the longer retention, but probably not all, because the summer plume velocity was slower by a factor of 1.6, while summer short-term retention was 2.8 times that of winter. Biomass in the stream, including macrophytes, epiphytes, and epilithon, was higher in the summer than winter, favoring increased summer P uptake. Water temperature differed markedly between the two experiments and it seems likely that higher summer water temperatures influenced the higher summer retention. Short-term retention in both experiments reached a maximum at the highest P concentration in water, i.e. the highest gradient between water and other compartments. Thus, in addition to temperature, it seems that the short-term retention was also related to concentration gradient.

The short-term retention in both attenuation experiments probably resulted from a combination of sorption by inorganic sediments and by organic biofilms. The high capacity of sediments to adsorb P from the water column was demonstrated by the sediment P adsorption/desorption experiments discussed earlier in Section 3.3.7. P concentrations in LaPlatte River sediments were well below saturation and sediment immersed in solutions with high P concentrations removed substantial quantities of P. About half the total adsorption took place quickly, in less than 1 hour. In contrast, sediments placed in low P water released some P into solution. Thus, the sorption reaction appears partially reversible and adsorption of P from high P concentration water and release of P into low-P water is consistent with the concept of sediment adsorbing P from water during the passage of a plume of high-P water followed by release to water at background P concentrations after the plume had passed in the attenuation experiment. P release from river sediments has been documented under both aerobic and anaerobic conditions (Kleeberg and Schlungbaum 1993).

While epilithon were probably present in small amounts under the ice during the winter attenuation experiment, their growth was probably minimal so active P uptake was likely small. However, passive P adsorption by the periphyton matrix (slime and entrapped fines) was shown to account for 20 - 40% of total epilithon uptake in this study and even higher proportions in other studies (Lock 1979) and could account for some of the short-term uptake. The degree to which such uptake is reversible or the rate at which release could occur, however, is unknown.

The higher short-term retention in the summer experiment could be attributed to higher temperatures, which would tend to increase rates of sorption by sediment (Holtan et al. 1988) and the epilithic matrix, to increased contact time due to lower water and plume velocities, or to additional uptake mechanisms, such as active uptake by epilithon, macrophytes, or epiphytes which were far more abundant in summer, and which would have been enhanced by higher temperatures.

About 30% of the added P was retained in the stream in the summer attenuation experiment. This retention was distinct from the short-term retention observed in both experiments because it lasted at least to the end of the 40-hour experimental period. Potential P flux to sediments was measured in the macrophyte microcosm experiments, showing rates as high as 173 mg/m^2/day under elevated SRP concentrations in water (see Table 3.21).

Uptake by epilithon could have been a major factor in this retention. Epilithon biomass was high in the LaPlatte and appropriate substrate was abundant in the 3 km reach. Measured P flux into epilithon was appreciably higher than reported for most other stream systems. The average P uptake rate for epilithon measured in flux experiments (Section 3.3.1) was 66 mg P/m^2/day, more than enough to account for the estimated 25 mg P/m^2

taken up during the experiment. In other flux experiments in this study, P uptake by macrophytes and epiphytes was greatly stimulated by addition of P to water, accounting for up to 170 mg P/m^2/day in summer where plants were abundant (see Table 3.21).

Other studies have pointed to similar overall uptake rates and vectors. Hill (1982) reported retention of 11-21 mg SRP/m^2/day in Ontario streams. Mulholland et al. (1990) suggested that biologically mediated uptake was most important at SRP concentrations below 5 µg/L, while physical/chemical sorption occurred at higher ambient P levels and continued to increase with increasing concentration. Munn and Meyer (1990) measured SRP uptake of 3 - 22 µg/m^2/min (4 - 32 mg/m^2/day) in just a 20 m stream reach in North Carolina and attributed most of the uptake to biotic processes, including microbial and epilithic uptake. Hart et al. (1992) reported retention of more than 10 mg P/m^2/day (32% of added P) in a 32 m reach of an Australian stream and attributed most of the retention to sediment uptake, both chemical sorption and microbial.

It must be cautioned that our attenuation experiments were done at P concentrations well above ambient levels (i.e. >0.2 mg P/L compared to background concentrations of 0.05 - 0.1 mg P/L). Microcosm experiments in this study have shown that disturbance of steady-state conditions by P addition can significantly increase benthic uptake. The results of the attenuation experiments may not , therefore, be completely representative of P dynamics under "normal" conditions. The elevated concentration gradients probably influenced water-sediment interactions and may have affected biological uptake patterns. Mulholland et al. (1990) , for example, stated that PO_4 releases will overestimate P uptake length unless the PO_4 concentration increase is small enough to avoid saturating the biological community. However, the biological community in the LaPlatte, particularly epilithon, was much more dense than in the forested first-order streams usually cited in the literature, and thus less prone to becoming saturated. Furthermore, even elevated P concentrations are useful for estimating uptake *potential*, and to assess stream response to disturbance. It is worth noting that storms could result in P additions of comparable magnitude from nonpoint source runoff.

It is impossible to extrapolate from two attenuation experiments conducted at low flows over 3 km to annual behavior of a whole stream system. Seasonal influences are likely to be large, with higher temperatures and plant production suggesting higher potential retention in summer. Certainly, hydrology is a driving force in determining P retention in a stream. Stream discharge alone is the primary determinant of downstream P flux. Reduced contact times between the water mass and the stream substrate resulting from higher velocities during stormflow would tend to reduce potential P uptake in the stream system. Meyer and Likens (1979) determined that net P retention in a New Hampshire stream was extremely variable in summer months, with low retention during years of major storms and high retention during years dominated by base flow. They observed that P was stored in the stream during most of the year, punctuated by short bursts of P loss during high flow events, leading to little or no net annual retention, and suggested that P flux through the stream was predictable from hydrologic information alone, while in-stream P processing was consistent on an annual basis.

However, the work of Meyer and Likens was done in an undisturbed headwater stream and may have limited applicability to enriched lowland streams such as the LaPlatte. In fact, several points in this study contradict the points raised above. Significant differences in P behavior were observed between the two attenuation experiments, even though both were done under generally comparable hydrologic conditions. Differences in magnitude and duration of short-term retention between the summer and winter experiments and the demonstration of long-term retention only in summer suggest that in-stream P processing was not consistent between the two seasons. Furthermore, it was noted that the high-flow event of August 1994 actually stimulated higher P uptake by epilithon, rather than simply increasing downstream P flux.

Finally, it is interesting to speculate on the potential significance of seasonal and hydrologic variations in in-stream P processing observed in this study. Our data have indicated, for example, that P uptake and retention tended to be higher during warm weather low flows in the period of active plant growth, and lower during winter at low temperatures. Higher flows, especially spring runoff, would be expected to also result in low retention and uptake, with very short water contact times under high discharge. However, this pattern is tempered by the observed increased P uptake in the stream in response to elevated P concentrations in water and to moderate increase in flow associated with the small summer storm event. These observations begin to suggest that in-stream P retention processes may have the greatest potential to attenuate spikes of P delivered to the stream in small stormflows during the growing season, i.e. nonpoint source events, rather than the more continuous P discharge associated with point sources or with the massive hydrologic flux of snowmelt and spring runoff. Because the majority of the annual P load to Lake Champlain tends to be delivered with spring runoff, such warm-weather P retention in streams may be of relatively low importance to overall phosphorus load in Lake Champlain Basin tributaries. However, in-stream processes resulting in attenuation of P load to the lake in the summer is precisely the time when algae in the lake are likely to respond to P additions.

4.3 WHOLE RIVER CONJECTURES

Rigorously estimating whole river P stocks would require a systematic sampling of the various stream orders comprising the LaPlatte River surface water network. Short of this, some approximation of the potential P storage in biotic and abiotic pools in the river as a whole can be calculated using ranges of values for P stocks per unit area of our study reaches extrapolated to the entire stream surface. This rough calculation, however flawed, can provide some perspective as to the comparative potential of in-stream processes in control P concentrations in the stream.

As noted earlier (Section 3.1.1) stock of total P in water is negligible relative to the other stock components. The P stock in sediment is the largest single component, followed by epilithon, macrophytes, and detrital pools (Table 3.14). The total P stock (study average) ranged from 2.8 g/m^2 at the cobbly Spear St.site to 33 g/m^2 at the Bacon Dr. site with its finer grained sediments. This order of magnitude range can provide some boundaries to the potential P stored in the river as a whole. If the entire river was cobbly then the P stock could be estimated as 2.8 g/m^2 X 510,000 m^2. In like manner if the entire stream were made up of finer grained sediments then the multiplier could be 27 g/m^2. These speculations yield a range of from 1.4 to 14 Mg of P in the entire LaPlatte River. Because it is unlikely that the river is dominated by either of these extremes, the actual P content of the river probably lies closer to the midpoint between this range. Sediment concentrations may vary from the observed concentrations reported in this study, making the more important variable sediment storage of P as opposed to sediment type (size class distribution, composition, etc.).

If the total river stock of P is estimated to be around the midpoint of the range obtained above, this value of roughly 8Mg compares well with the estimated annual output of P from the river of 7.6 Mg/yr (VT DEC and NYS DEC 1994). The role of in-stream storage and release in controlling P concentrations in the stream is related to the change in P storage pools over time. The maximum difference in measured P stocks over the course of this study for the Bacon Dr. and Spear St.sites was 7.5 g/m^2 and 3.3 g/m^2, respectively (Table 3.14). Making similar assumptions to extrapolate these values to the whole river, from 1.7 Mg to 3.8 Mg of P might be taken up or released by in-stream abiotic + biotic processes. Again, these values compare favorably with the estimated annual P flux for the river suggesting that the change in P storage in the river system could substantially alter the measured annual flux of P from the 13,800 ha basin to Lake Champlain. However, this potential influence on stream water P concentration could not be sustained over a series of years without an accompanied cumulative change in sediment P concentration.

4.4 DYNAMIC SIMULATION PHOSPHORUS MODEL (DSPM)

There are a number of conclusions (and cautions) that may be made with regard to the development of this initial version of the DSPM.

1. This initial version of the DSPM has been tested extensively during its development and it is believed that it competently reflects P cycling, transformation and transport through stream reaches. In other words, the behavioral patterns demonstrated by the DSPM model do appear to follow field observations and appear to conform to theoretical expectations.

- **Additional work is needed to verify the DSPM in another river system.**

2. This initial version of the DSPM is a complex description of the very complicated behavior of the cycling, transformation and transport of P in stream reaches. Because of the complexity of this model and its consumptiveness of computer resources , it does not possess the ability to continuously evaluate P transformations and transport over a full annual cycle with the computer resources typically available at the desk top level. (However, see Section 3.6.2 for the way this was accomplished in this study). The DSPM is useful for describing the dynamics of P cycling, transformation and transport over

shorter periods of time, the length dependent upon the extent of computer resources available.

- **Further development of DSPM is needed to extend the period of time over which simulations can be carried out.**

3. The initial version of the DSPM assumes that the volume of water within the reach is completely mixed at all times. With this simplifying assumption the DSPM model cannot perfectly represent reality with regard to the mixing regime typically observed in stream reaches. To account for the non-complete mixing within a stream reach will substantially increase the complexity of the DSPM.

- **Further development of DSPM is needed to incorporate algorithms that may better describe the real mixing conditions in stream reaches.**

4. This initial version of the DSPM allows the user to easily change inputs so that simulation runs can be run over a wide variety of stream flow and P concentration conditions during summer or winter periods. Additionally, inputs can be varied to allow the user to define stream reaches and carry out simulations for stream reaches having widely different characteristics. The DSPM can thus simulate P cycling, transformation and transport for many of the stream flows and stream reaches found in the Lake Champlain Basin.

- **Further field work is needed to compare model outputs to a wide variety of stream reach conditions.**

5. When using the DSPM to simulate P cycling, transformation and transport in the Spear Street and Bacon Drive reaches in the LaPlatte River, the estimated proportion of the TP

contained within the various TP storage compartments parallelled the findings of the field studies.

6. When using the DSPM to simulate P cycling, transformation and transport a number of questions and issues arose concerning our understanding of the manner in which real streams may function to process P. These include:

a.) The DSPM estimates the <u>potential</u> for the LaPlatte River to transport both suspended and bedload sediments. Various model simulations suggest that there is an interaction between the sediment transported as bedload, the sediment suspended in the water and the sediment captured in the epilithon biomass. There is little information available on this possible set of interactions.

b.) The DSPM simulations suggest that P incorporated into the periphyton and the macrophytes is stored in those compartments for periods of weeks and cannot explain long term storage of P in the ecosystem. The sediment compartment is the only compartment that appears to have any potential for long term P storage in stream reach ecosystems.

c.) The erosion and movement of sediments and detached organic materials such as periphyton and macrophyte biomass may represent a major source of TP flux in a stream reach. Very little is known about the physics of the detachment (sloughing and abrasion) of periphyton and macrophytes. Little is known of sediment movement in stream and river systems typical of the Lake Champlain Basin.

7. Given the full features of the STELLA II software, this initial version of the DSPM will permit the researcher to explore how individual P cycling and transport processes interact within a stream reach and will thus promote the understanding of how P moves through watershed and stream and river systems.

8. The DSPM, as presented here, is believed to provide an initial basis for a management tool that could ultimately assist managers assess alternative scenarios for P management in watershed and stream systems. However, incorporation of the DSPM into the management environment as a productive tool will require additional cooperative efforts by managers and researchers.

4.5 MANAGEMENT IMPLICATIONS OF P DYNAMICS IN THE LAPLATTE RIVER

The Lake Champlain Management Conference will need to make critical decisions on how best to achieve desired reductions in P loading to Lake Champlain. In order to support such decisions, the Management Conference sought insight on several key issues with regard to P loading to the Lake:

> 1) What are the important factors in determining which sources of P should be targeted for treatment efforts, e.g. is distance from the Lake important;
>
> 2) What is the lag time between reduction efforts on the land and downstream response in water quality; and
>
> 3) What are the critical factors controlling P transport and transformation in streams draining to Lake Champlain?

While the results of this project cannot provide definitive answers to these questions for the Lake Champlain Basin, we can apply our conclusions from the LaPlatte River to shed some light on these questions.

A central finding of this study was that stream reaches with different flow rates and different biotic and abiotic characteristics store and process P differently. While the <u>mechanisms</u> of storage and processing, e.g. sediment adsorption, plant uptake, are the same in different stream reaches, the relative importance of different stocks and processes, and hence the overall impact of a reach on the transport of P downstream differ significantly. Phosphorus concentrations were also found to be critical influences on the rate of P flux between water and sediments, epilithon, macrophyte, and epiphyte compartments, individually and on net uptake during P pulses. Both field/lab data and model predictions support these points. Therefore, while distance (or time of travel) is likely to be one important determinant of net P transport, managers are advised to consider not only basic distance of sources upstream but also the characteristics of the stream reaches lying between the source and the stream mouth. Phosphorus retention and attenuation is not likely to be a simple function of stream length. The DSP Model developed in this project can be used to predict P transport and retention in different stream reach types and segments of different reach types can be linked in sequence to access a longer, heterogeneous stream system.

Firm conclusions with regard to probable lag times between source reduction and tributary load reduction are beyond the scope of this study. A lag in system response to reduced P inputs from upstream could result from release of P stored in sediments, plants, or detritus, essentially a buffering phenomenon. Because sediments were shown to be by far the largest reservoir of P in the stream system, and because sloughing and senescence of plants and epilithon are likely to release stored P within the same annual cycle where uptake occurred, any major lag time would probably have to involve the sediments. Laboratory studies in this project showed release of P from sediments was much slower than adsorption, supporting the possibility of a lag phenomenon, although this is difficult to extrapolate to the field scale. Perhaps the most intriguing hint of a significant lag is found in the significantly lower P concentrations in water observed during this study compared to those observed in the 1980s; P stocks in water and sediment appeared to decline even within the two years of this study. Given the observation that sediments in our stream reaches were not saturated with respect to P and that the P load in the discharge from the Hinesburg treatment plant dropped dramatically in 1992, we speculate that the sediments in the LaPlatte may still be releasing P stored from the period before 1992, essentially buffering the levels of P in the stream system. Such a scenario would suggest a lag time in excess of three years for the 15 km of the LaPlatte River between the Hinesburg treatment plant and Bacon Dr.

Biotic factors were clearly important in P retention in our study reaches, at least seasonally. The rich epilithon community was active in P uptake, as were macrophytes and epiphytes where they were abundant. Passive uptake by biofilms (the thin biological "slime" layer that coats all submerged surfaces, that also includes periphyton under conditions of adequate light) and capture of suspended fine sediment by epilithon were also important biotic P uptake pathways. In contrast, the relative scarcity of organic matter input from trees reduced the importance of detritus in this system. Abiotic factors were also important. Physical factors such as flow and substrate type determine what sediments, epiphytes, and macrophytes may be present in any given stream environment. Ambient P concentrations were also important, as illustrated by enhanced uptake of P by epilithon, macrophytes, and epiphytes under high P levels and by the observed uptake rates associated with maximum P concentration gradient during both attenuation experiments. Differences between the two attenuation experiments suggested that flow, temperature, and water travel time may be important factors in P retention in a reach. High flows are obviously important forces, particularly with regard to the ability to resuspend and transport fine sediments and wash out plant material, although the moderate high flow episode we studied actually enhanced epilithic P uptake. Again, we emphasize that numerous other factors influence net P transport in addition to distance.

What do these factors mean to Lake Champlain? We believe that the in-stream system cannot be a permanent or even very long-term repository for phosphorus. Even P strongly adsorbed by stream sediments can be transported by high flows and delivered to the Lake where the potential exists for re-release from those sediments to lake water. Other vectors for P removal from stream sediments may also exist, such as uptake by macrophytes followed by senescence and transport.

However, the seasonal and hydrologic variations in in-stream P processing observed in this study may have significance for the impact of P loads to Lake Champlain. Even if, for example, the potential retention of P in biological communities and sediments during the summer, as illustrated by the summer attenuation experiment, is only seasonal, such retention could act to improve water quality at a critical time of year for the receiving water. Note that BAP flux from water to sediments was particularly high in radiotracer experiments, suggesting a greater potential influence on biologically available P. Further speculation suggests that in-stream P retention processes may have the greatest potential to attenuate spikes of P delivered to the stream in small stormflows during the growing season, i.e. during nonpoint source events, rather than during the more continuous P discharge associated with point sources or with the massive hydrologic flux of snowmelt and spring runoff. While such warm-weather P retention in streams may be of relatively low importance to the annual phosphorus load delivered to Lake Champlain by a tributary, in-stream processes resulting in attenuation of P load to the lake in the summer would occur at a time nearly optimal to control algal growth.

In considering options for improving water quality in the Lake Champlain Basin, management of the nutrients in the landscape as a whole becomes an important objective. The river network, as an important landscape component, can behave as a "capacitor" by storing and releasing phosphorus on different times scales than export from land and point sources are occurring. For the LaPlatte Basin, the potential river storage of P approximates one years export from land sources. Thus, the river, as it is currently configured, probably is not capable of longer term effects on P loading to the lake. Clearly, changes in the stream bottom character via increased sedimentation from poor land practices or stream bank management could change this relationship.

By far the greatest portion of the total P loading to the lake occurs during very high flow events. During these events the role of instream processes is probably diminished due to short time of travel, high sediment loads, and the scouring action of the high flows with its associated sediment and bedload. While, moderately high flows may deposit P rich sediment in the epilithon and macrophyte beds, higher flows can strip both of these components out of the stream bed and transport this P rich component to the lake. Subsequent sedimentation and biotic uptake in the "recovery" period may make the river a storage site until the next event.

To complement land management activities (reduction of agricultural inputs, BMPs, etc.), management of the stream hydrologic regime can assist in reducing stream P loading. Maintaining forested cover to keep watershield yields low, ameliorating stormflow peaks, and increasing evapotranspiration in riparian areas where runoff source areas predominate can all aid in reducing both P loading to surface water and the movement of stream sediments to the lake.

The current emphasis of research and management is on total P. While clearly important in assessing P loading and allocating resources to management activities, our research suggests that P form in the LaPlatte varies considerably over the course of the year. If much of the total P is being transported to the lake to be buried in accumulating sediments, then other forms of P may be more important to consider relative to concerns about eutrophication of the lake. The potential role of instream processes seems apparent given our measurements of BAP and SRP. Maintaining a productive river substrate for epilithon and macrophytes may aid in reducing more available forms of P at times (late growing season) when its effect on lake processes may be most problematic.

In conclusion, based on the results of this project, we cannot recommend to the Lake Champlain Management Conference that simple distance to the Lake be employed as the primary criterion for targeting P reduction efforts. Many other factors are important in controlling in-stream P dynamics; stream environment type, flow, and season may, for example, be far more important determinants of P delivery than distance alone. Our data on P form were too inconsistent to conclude that phosphorus form is consistently changed in transit to the Lake. We believe the most reasonable course of action is to assume that all in-stream P will be delivered to Lake Champlain within the planning horizons of the Management Conference.

4.6 FUTURE WORK

The present investigation has provided significant insight into processes of phosphorus transport and transformation within stream reaches including both the relative magnitude of P storage within various compartments and the rates of movement between compartments. It has identified critical factors affecting storage and release of P as well as providing a model framework for management decisions. This study also identified critical areas in which information is lacking or insufficient. In order to fully understand the behavior of phosphorus within streams, we make the following recommendations for future work.

While major emphasis of the present investigation was to delineate the relative importance and processes occurring within specific P storage compartments, it is clear that the boundaries of the specific compartments are not clearly defined and that there is often a synergy between these compartments. Additional research is needed to more accurately determine the nature of interactions and rates of exchange within and between P repositories in fluvial systems. For example biofilms, the biological layer that coats all surfaces within streams and includes those surfaces that receive sufficient light that algae are the dominant component (e.g. epilithon, epiphyton) are present in all substrate compartments. Future work should investigations of :

- The role of biofilms on all surfaces in P dynamics including:
  - Seasonal dynamics of biofilm surfaces
  - Controls of thickness and activity
  - Sterilized vs. unsterilized experiments of P storage and transformations within and between compartments
- The interaction between periphyton (both epiphytes and epilithon) and sediment including:
  - The importance of periphyton as traps for fine suspended sediment
  - The importance of trapped fine sediments as a nutrient source for periphyton
  - Sloughing of periphyton and release of trapped sediment as a function of flow
- The role of passive vs active uptake of P by periphyton particularly with respect to turnover rates and kinetics with increasing P concentration
- The interactions between macrophytes and epiphytes in P uptake storage and release.
- Microbial effects on P storage, release and transformations within all compartments
- Effects of grazing on periphyton P cycling
- Turnover rates of P taken up by epilithon, macrophytes and epiphytes
- The role of in-stream processes in the transformation of P bioavailability

- The role of macrophyte beds on flow and transport of P including sediment trapping, enhanced uptake and storage from water, as a substrate for epiphytes, etc.
- The extent to which macrophyte detritus is buried vs. carried downstream
- The effectiveness of plant P translocation of P to roots prior to fall senescence with subsequent P storage in roots over winter

This study clearly demonstrates the relative importance of sediments as a repository of P. Various microcosm and adsorption-desorption experiments indicate the potential for sediments to function as either a source or sink for P in fluvial systems. Future work to better define the role of sediment-water interaction should include:

- Rates, directions and controls on P sorption/desorption from bottom sediments including:

  In-situ rate measurements

  Reversibility of adsorption-desorption

  Microcosm studies to control specific variables (flow, concentration, temperature, pH, etc.)

  Sterilized vs. unsterilized sediment studies to distinguish biological uptake from true adsorption

  Adsorption/desorption of P species other than orthophosphate
- Depth of interaction between surface water and sediments, surface water and sediment pore water and controls thereof, including exchange of water and/or P with hyporheic zone
- Role of bedload sediment transport and deposition in P transport and storage

- Relationships between suspended solids and P cycling and transport including:

    Sorption/desorption of P by suspended solids

    Transformations of P associated with suspended solids

    Incremental movement of sediment-bound P with suspended solids

- Examination of out-of-bank processes (floodplain deposition and/or erosion) for long-term P storage or input

The attenuation experiments as well as routine determination of P within the water compartment indicate that some P is stored within the reach, at least within the time framework and analytical capabilities employed. Future work should include:

- Additional attenuation experiments to:

    Examine attenuation under other seasonal and/or flow conditions such as spring runoff, summer stormflows etc.

    Extend the length of the study reach

    Improve documentation of stream environments within attenuation reach

    Examine transformations among P forms (e.g. BAP, SRP etc) during experiments

- Short term retention and uptake observed in both attenuation experiments
- Long-term retention of P observed during the summer attenuation experiment including

    Duration of retention

    Fate of retained P

- Increased reach length and/or increased analytical sensitivity to determine minimum contact time required for net change in water P concentrations

- Effects/determination of connectivity between stream and shallow groundwater and/or hyporheic zone

In addition to the aforementioned suggestions for future work there are some fundamental questions regarding scale and the interpolation/extrapolation of results which include:

- What are the effects of temperature, concentration gradients and flow on storage and transformation within and between all compartments?
- Can the results of a particular study be scaled up or down to predict results within reaches of different size, characteristics?
- Are scaling functions simple weighted averages or a more complex function?
- How does flow (especially high flow) affect rates and processes; which of these rates/processes are a continuous function of flow, which require specific threshold values?
- How does trophic status, substrate characteristics, and fundamental hydrologic characteristics affect transport and transformation processes? To what extent can studies of one reach be extrapolated to other reaches?
- How can specific species of P be measured/quantified? Most analytical techniques provide an operational definition of P, whereas rates and endpoints of most chemical and biological reactions are probably controlled by concentrations of specific P species such as orthophosphate.

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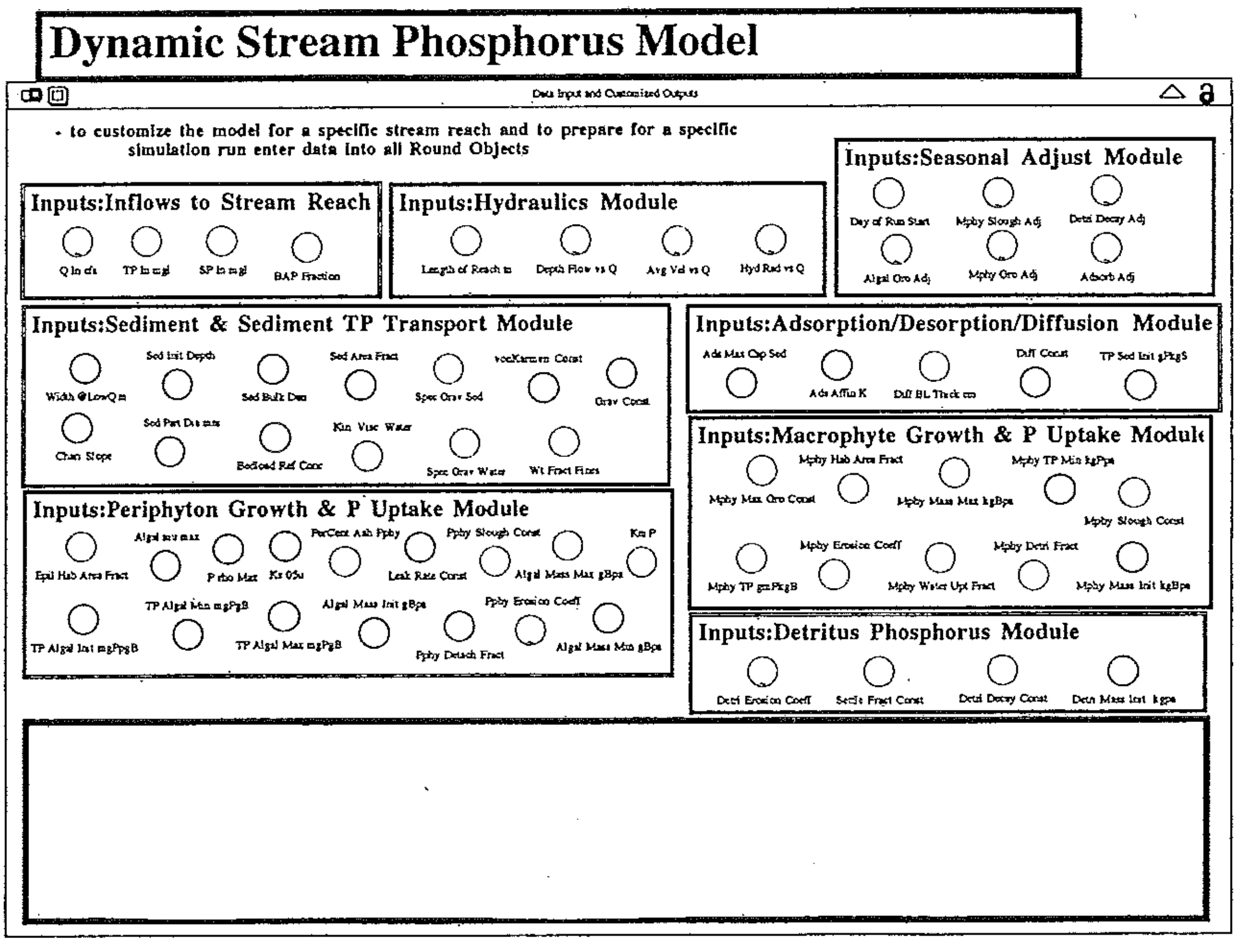
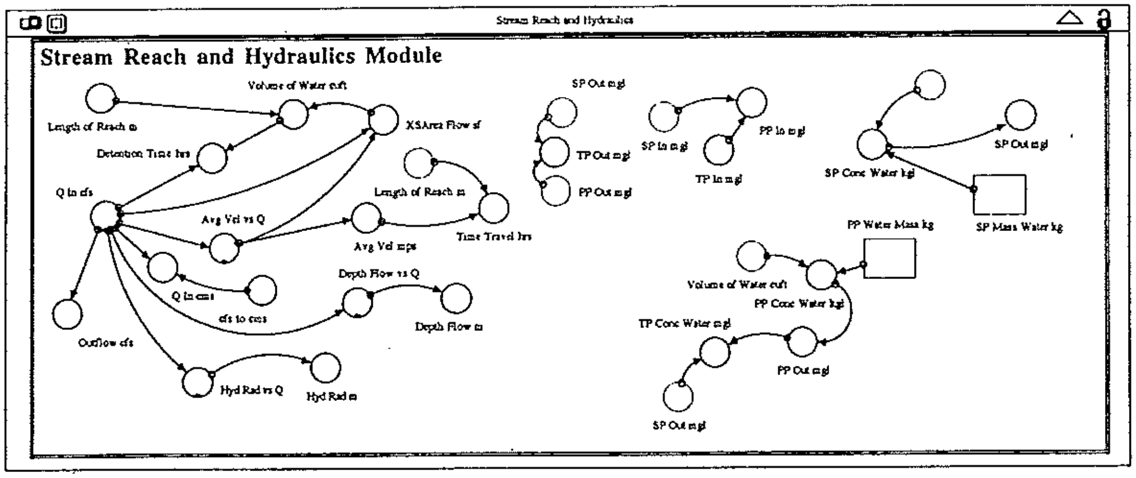
APPENDIX

APPENDIX A

Structural Diagram of the DSPM




Stream Reach and Hydraulics
Stream Reach and Hydraulics Module
Length of Reach m
Volume of Water cuft
XSArea Flow sf
Detention Time hrs
Q In cfs
Avg Vel vs Q
Avg Vel mps
Length of Reach m
Time Travel hrs
Q In cms
cfs to cms
Depth Flow vs Q
Depth Flow m
Outflow cfs
Hyd Rad vs Q
Hyd Rad m
SP Out mgl
TP Out mgl
PP Out mgl
SP In mgl
PP In mgl
TP In mgl
SP Conc Water kgl
SP Out mgl
SP Mass Water kg
PP Water Mass kg
Volume of Water cuft
PP Conc Water kgl
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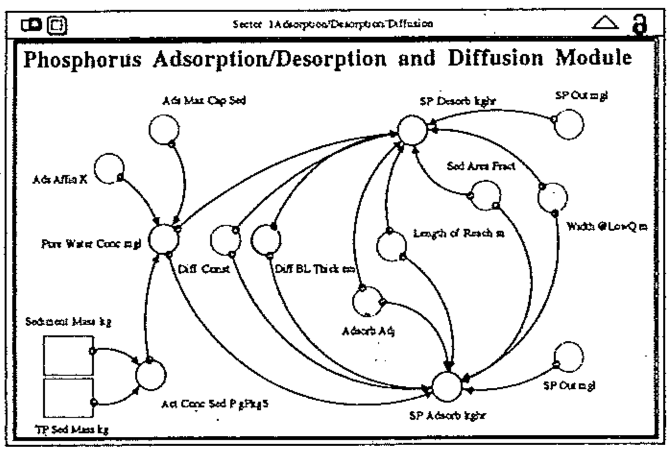
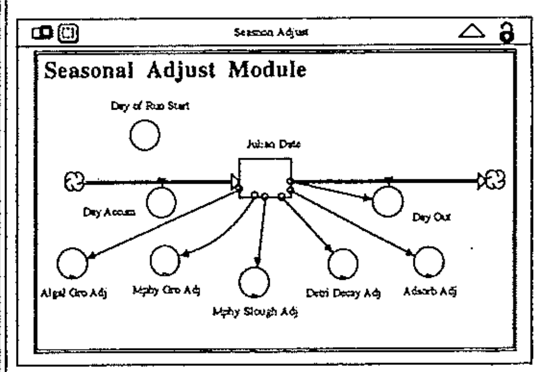
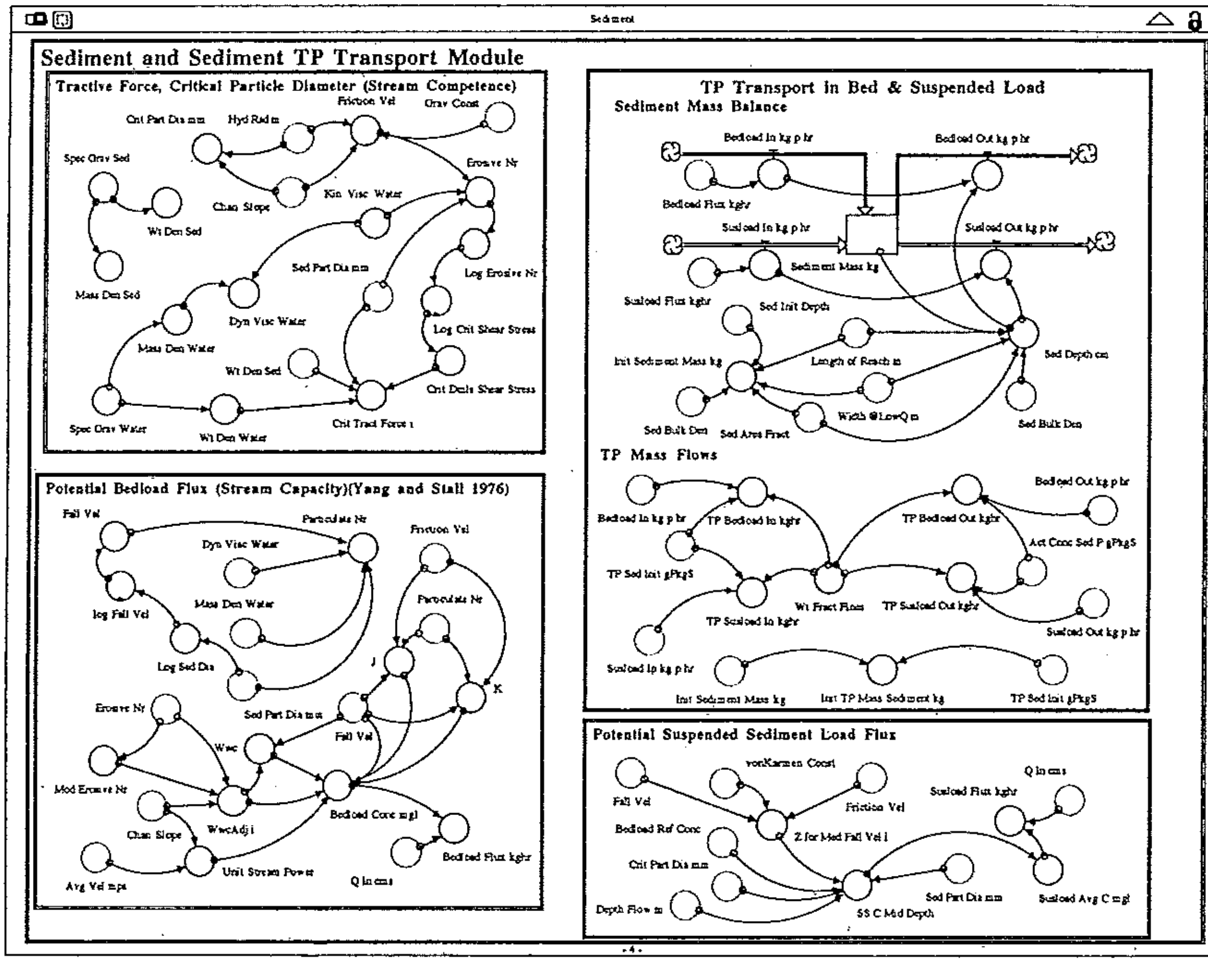
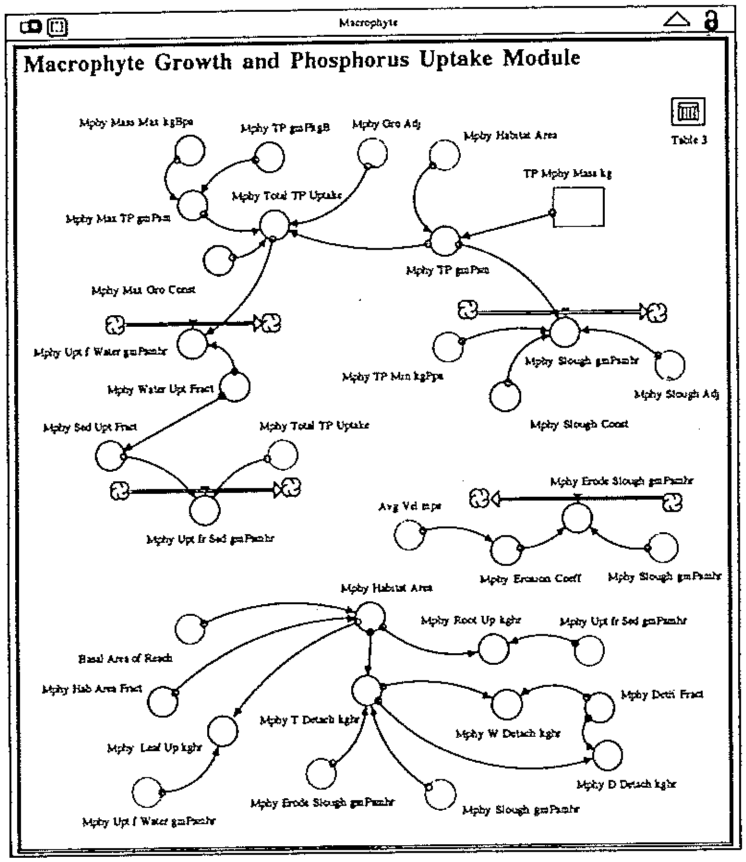
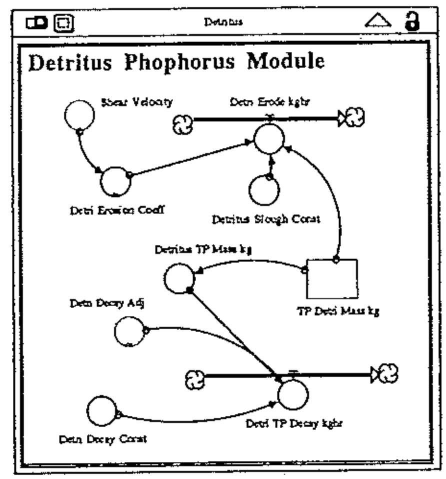
PP Out mgl
SP Out mgl

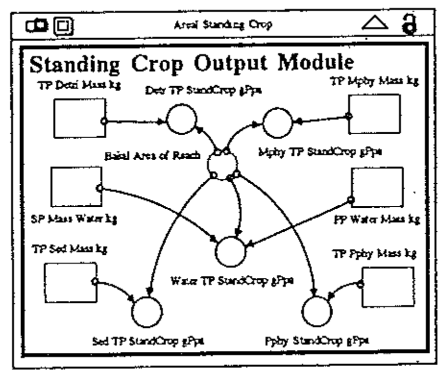

Phosphorus Adsorption/Desorption and Diffusion Module
Ads Max Cap Sed
Ads Affin K
Pore Water Conc mgl
Diff Const
Diff BL Thick cm
SP Desorb kghr
SP Out mgl
Sed Area Fract
Length of Reach m
Width @LowQ m
Adsorb Adj
Sediment Mass kg
Act Conc Sed PgPkgS
TP Sed Mass kg
SP Adsorb kghr
SP Out mgl


Season Adjust
Seasonal Adjust Module
Day of Run Start
Julian Date
Day Accum
Day Out
Algal Gro Adj
Mphy Gro Adj
Mphy Slough Adj
Detri Decay Adj
Adsorb Adj

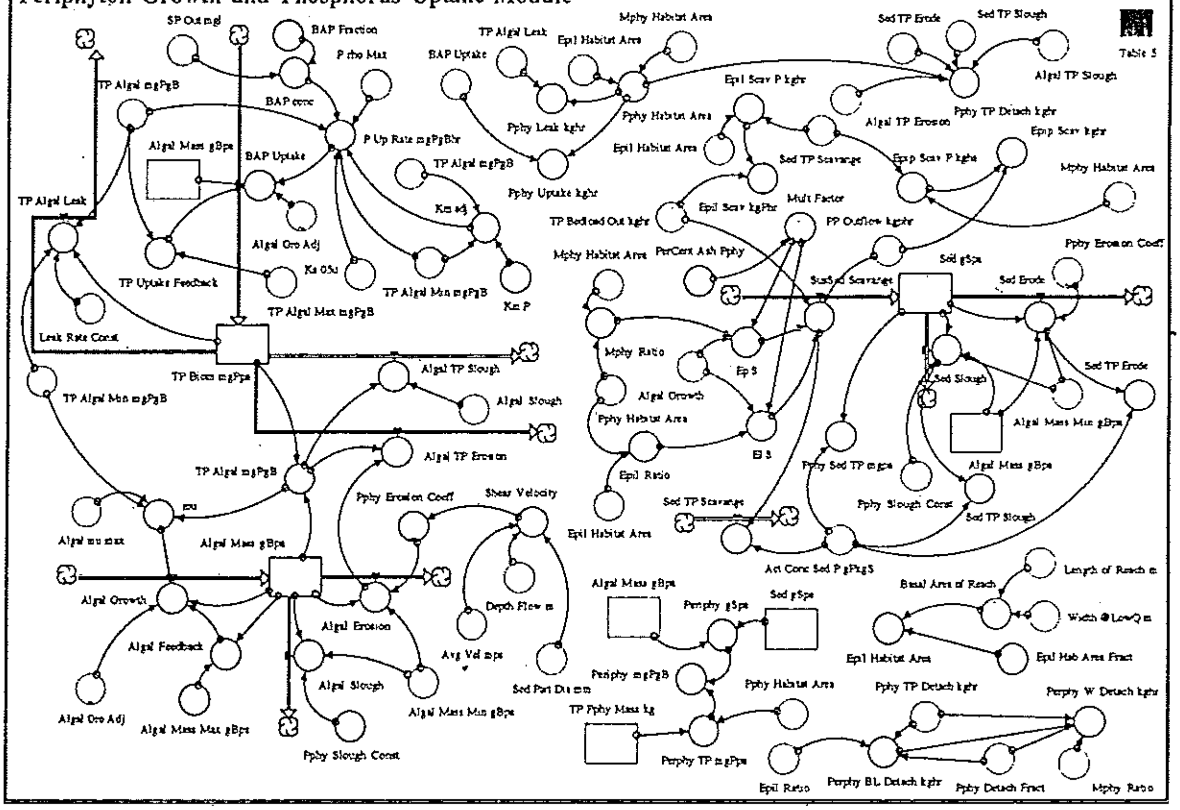

Sediment and Sediment TP Transport Module
Tractive Force, Critical Particle Diameter (Stream Competence)
Potential Bedload Flux (Stream Capacity)(Yang and Stall 1976)
TP Transport in Bed & Suspended Load
Sediment Mass Balance
TP Mass Flows
Potential Suspended Sediment Load Flux

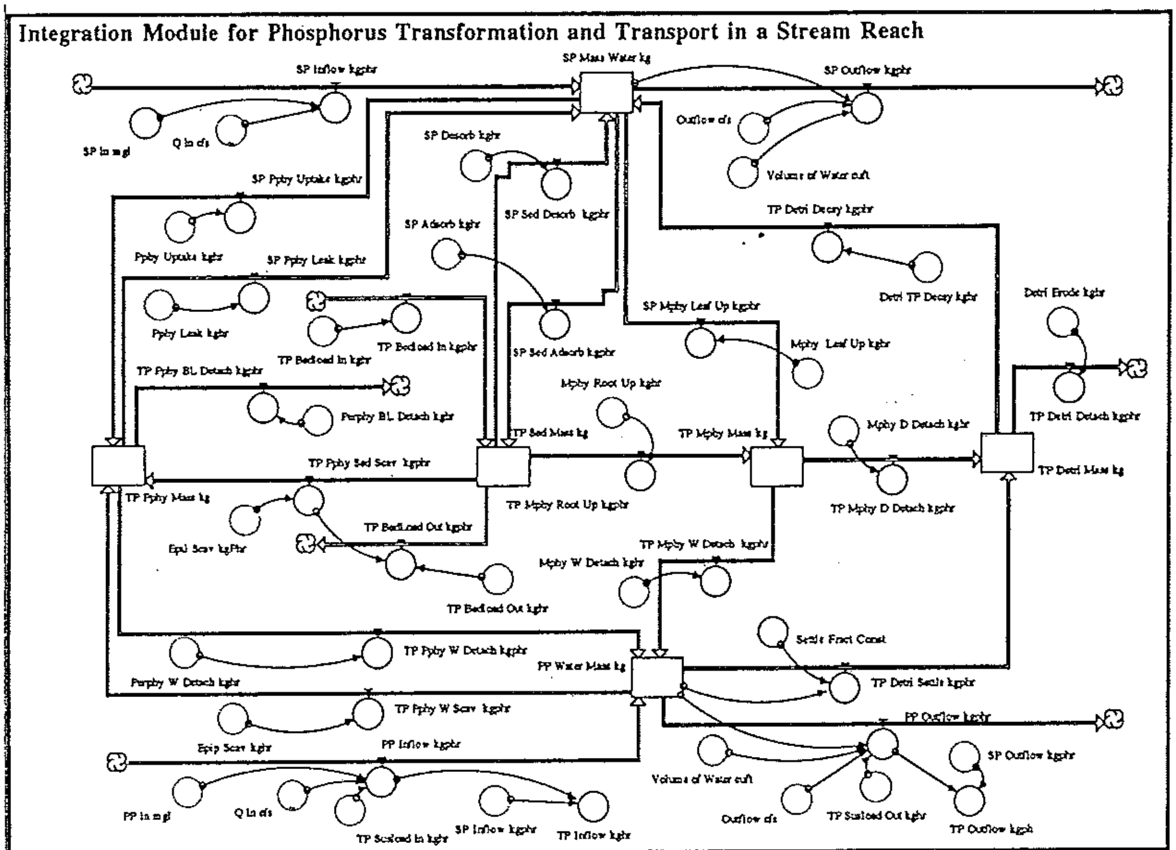

Macrophyte
Macrophyte Growth and Phosphorus Uptake Module
Table 3
Mphy Mass Max kgBpa
Mphy TP gmPkgB
Mphy Gro Adj
Mphy Habitat Area
TP Mphy Mass kg
Mphy Max TP gmPsm
Mphy Total TP Uptake
Mphy TP gmPsm
Mphy Max Gro Const
Mphy Upt f Water gmPsmhr
Mphy Water Upt Fract
Mphy TP Min kgPpa
Mphy Slough gmPsmhr
Mphy Slough Adj
Mphy Slough Const
Mphy Sed Upt Fract
Mphy Total TP Uptake
Mphy Upt fr Sed gmPsmhr
Avg Vel mps
Mphy Erode Slough gmPsmhr
Mphy Erosion Coeff
Mphy Slough gmPsmhr
Mphy Habitat Area
Mphy Root Up kghr
Mphy Upt fr Sed gmPsmhr
Basal Area of Reach
Mphy Hab Area Fract
Mphy Detri Fract
Mphy T Detach kghr
Mphy W Detach kghr
Mphy Leaf Up kghr
Mphy D Detach kghr
Mphy Upt f Water gmPsmhr
Mphy Erode Slough gmPsmhr
Mphy Slough gmPsmhr


Detritus
Detritus Phophorus Module
Shear Velocity
Detri Erode kghr
Detri Erosion Coeff
Detritus Slough Const
Detritus TP Mass kg
Detri Decay Adj
TP Detri Mass kg
Detri TP Decay kghr
Detri Decay Const


Areal Standing Crop
Standing Crop Output Module
TP Detri Mass kg
Detr TP StandCrop gPpa
TP Mphy Mass kg
Basal Area of Reach
Mphy TP StandCrop gPpa
SP Mass Water kg
PP Water Mass kg
TP Sed Mass kg
TP Pphy Mass kg
Water TP StandCrop gPpa
Sed TP StandCrop gPpa
Pphy StandCrop gPpa

Periphyton Growth and Phosphorus Uptake Module




Integration Module for Phosphorus Transformation and Transport in a Stream Reach
SP Inflow kgphr
SP Mass Water kg
SP Outflow kgphr
Outflow cfs
Volume of Water cuft
Q In cfs
SP Desorb kghr
SP Sed Desorb kgphr
SP Pphy Uptake kgphr
Pphy Uptake kghr
SP Pphy Leak kgphr
SP Adsorb kghr
TP Detri Decay kgphr
Detri TP Decay kghr
Detri Erode kghr
Pphy Leak kghr
TP Bedload In kgphr
TP Bedload In kghr
SP Sed Adsorb kgphr
SP Mphy Leaf Up kgphr
Mphy Leaf Up kghr
TP Pphy BL Detach kgphr
Perphy BL Detach kghr
Mphy Root Up kghr
TP Sed Mass kg
TP Mphy Mass kg
Mphy D Detach kghr
TP Detri Detach kgphr
TP Detri Mass kg
TP Pphy Sed Scav kgphr
TP Pphy Mass kg
TP Mphy Root Up kgphr
TP Mphy D Detach kgphr
TP BedLoad Out kgphr
TP Bedload Out kghr
TP Mphy W Detach kgphr
Mphy W Detach kghr
Settle Fract Const
TP Pphy W Detach kgphr
PP Water Mass kg
TP Detri Settle kgphr
Perphy W Detach kghr
TP Pphy W Scav kgphr
PP Outflow kgphr
Epip Scav kghr
PP Inflow kgphr
SP Outflow kgphr
PP In mgl
TP Scaload In kghr
SP Inflow kgphr
TP Inflow kghr
TP Scaload Out kghr
TP Outflow kgph

APPENDIX B

DOCUMENTED CODE for the DSPM

The code presented below is for simulation 1 (Spear St., summer). See Table 3.6.1.A for the specific conditions of this simulation. Output from this simulation, and simulations 2 and 3, are presented as original STELLA graphs following the documented code.

Areal Standing Crop

Detr_TP_StandCrop_gPpa = (TP_Detri_Mass_kg*1000)/Basal_Area_of_Reach
Mphy_TP_StandCrop_gPpa = (TP_Mphy_Mass_kg*1000)/Basal_Area_of_Reach
Pphy_StandCrop_gPpa = (TP_Pphy_Mass_kg*1000)/Basal_Area_of_Reach
Sed_TP_StandCrop_gPpa = (TP_Sed_Mass_kg*1000)/Basal_Area_of_Reach
Water_TP_StandCrop_gPpa =
((PP_Water_Mass_kg+SP_Mass_Water_kg)*1000)/Basal_Area_of_Reach

Data Input and Customized Outputs

Ads_Affin_K = 1000
DOCUMENT: Langmuir Isotherm Affinity Constant
- liters per gram P

Ads_Max_Cap_Sed = 0.25
DOCUMENT: Langmuir Isotherm Maximumadsorption capacity of sediment .
- gram P/kilogram dry sediment

Algal_Mass_Init_gBpa = 50
DOCUMENT: Initial Value for algal biomass per unit area of habitat in reach at the beginning of the simulation run.
- grams per square meter

Algal_Mass_Min_gBpa = 5
DOCUMENT: Min amount of dry algal biomass per area that can exist.
- grams dry algal biomass per square meter

Algal_mu_max = 0.015
DOCUMENT: Maximum periphyton algal growth rate constant.
- per hour

Bedload_Ref_Conc = 10
DOCUMENT: Reference Concentration of Bedload Sediment - the concentration of the bedload sediment at a distance of 0.05*Depth of flow above the sediment surface. Ranges from 0.5 (smaller particles) to 17 (larger particles) as per Vanoni (1975).
- grams per liter

Chan_Slope = 0.0085
DOCUMENT: Channel slope (S) -The slope is equal to the feet of elevation change along the channel bottom per foot of distance along the channel. Typically taken as an average slope over some length (reach) of the stream.
- (dimensionless -feet/foot)

Detri_Mass_Init__kgPpa = 6*10^-6

DOCUMENT: Initial value of the mass of Detrital P in the reach that exists at the beginning of he simulation run.
- kilograms of P pr square meter

Diff_Const = 10^-3
DOCUMENT: Diffusion constant (Fick'sFirst Law of Diffusion).
-square centimeter per second

Grav_Const = 9.8
DOCUMENT: Constant of Gravity - acceleration due to gravity.
- meters/second squared

Ks_05u = 1
DOCUMENT: Half saturation constant for phosphorus uptake as a funtion of internal phosphorus concentration.
- milligrams P per gram dry Algal Biomass

Leak_Rate_Const = 0.0001
DOCUMENT: Periphyton leak rate constant.
- per hour

Mphy_Mass_Init_kgBpa = 0.03
DOCUMENT: Initial value of mass per unit area in macrophytes in the reach that exists at the beginning of the simulation run (0.015 represents the over winter value) (the value of this initial value must be greater than the assigned minimum Mphy Biomass.
- kilograms per square meter

Mphy_TP_Min_kgPpa = 0.000008
DOCUMENT: Minimum permissable macrophyte TP per area - typically the amount that over-winters. (typical values might be in the range of 10 to 30 mg P/sq.m).
- kilograms P per square meter of macrophyte habitat

Pphy_Detach_Fract = 0.7
DOCUMENT: Fraction of Periphyton that when detached moves into the bedload, the remainder moves into the PP water compartment
- dimensionless

P_rho_Max = 0.1
DOCUMENT: Maximum phosphorus uptake rate per unit mass of algal biomass.
- milligrams P per gram dry Biomass per hour

Sed_Area_Fract = 0.07
DOCUMENT: Fraction of the stream bottom (basal area) that is covered with sediment.
- dimensionless

Sed_Bulk_Den = 1.75
DOCUMENT: Bulk density of the sediment - dry weight of the sediment per unit volume of sediment.
- (g/cu.cm.)

Sed_Init_Depth = 5
DOCUMENT: Average depth of the sediment over the bottom of the stream reach.
- centimeter

Sed_Part_Dia_mm = 0.5
DOCUMENT: Particle Diameter of the sediment - the diameter of the median particle size of the sediment in the stream bed. The critical size for interaction with the epilithon is silt and smaller. (Use 0.0625mm).
- millimeter

TP_Algal_Init_mgPpgB = 4
DOCUMENT: Initial value of P content of algal biomass that exists at the beginning of the simulation run.
- milligrams P per gram dry biomass

TP_Algal_Max_mgPgB = 8
DOCUMENT: Maximum P content of algal cells in periphyton.
- milligrams P per gram dry biomass

TP_Algal_Min_mgPgB = 0.6
DOCUMENT: Minimum concentration of P in algal biomass (Minimum cell quota).
- milligrams P per gram dry biomass

TP_Sed_Init_gPkgS = 0.35
DOCUMENT: The initial concentration of TP in the sediment at the beginning of the simulation run.
- grams P per kilogram dry sediment

vonKarmen_Const = 0.4
DOCUMENT: von Karmen's contant - assumed to be about 0.4 for open channel flow.
- dimensionless

Width_@LowQ_m = 11.5
DOCUMENT: Average width of the reach under low flow conditions.
- meters

Detritus

Detri_Erode_kghr = TP_Detri_Mass_kg*Detritus_Slough_Const*Detri_Erosion_Coeff
DOCUMENT: Flux of detrital TP detachment due to continuous sloughing and to erosion by high flow conditions.
- kilograms of P per hour

Detritus_Slough_Const = 0.01

Detritus_TP_Mass_kg = TP_Detri_Mass_kg

Detri_Decay_Const = 0.0008

Detri_Erosion_Coeff = GRAPH(Shear_Velocity)
(0.00, 1.00), (0.0125, 1.25), (0.025, 2.75), (0.0375, 3.70), (0.05, 4.95), (0.0625, 5.75), (0.075, 6.40), (0.0875, 7.00), (0.1, 7.35), (0.113, 7.70), (0.125, 7.95), (0.138, 8.05), (0.15, 8.15), (0.163, 8.10), (0.175, 8.10), (0.188, 8.10), (0.2, 7.85)
DOCUMENT: Sloughing is induced by increase in mean free-stream velocity, which increases the shear velocity, which in turn causes frictional shear forces to remove portions of the biofilm. The relationship expressed here between shear velocity and sloughing is partially derived from data from my experiments and partially derived by available literature on sloughing.

Macrophyte

Mphy_Erode_Slough_gmPsmhr = (Mphy_Slough_gmPsmhr*Mphy_Erosion_Coeff)
DOCUMENT: Flux of TP in macrophytes that is eroded by high flows.
- grams TP per square meter per hour

Mphy_Detri_Fract = 0.5
DOCUMENT: Fraction of the detached macrophytes that are moved into the detritus compartment. The remaining fraction is moved into the particulate P compartment.
- dimensionless

Mphy_D_Detach_kghr = Mphy_Detri_Fract*Mphy_T_Detach_kghr

Mphy_Erosion_Coeff = if (Avg_Vel_mps>=1.0) Then (10*(Avg_Vel_mps^3)) else 0
DOCUMENT: Relationship between average stream velocity and a factor that adjusts the rate at which macrophytes are eroded.
- average velocity in meters per second
- macrophyte erosion coefficient is dimensionless

Mphy_Habitat_Area = Basal_Area_of_Reach*Mphy_Hab_Area_Fract

Mphy_Hab_Area_Fract = 0.025
DOCUMENT: Fraction of basal area of the stream reach that is defined as macrophyte habitat.
- dimensionless

Mphy_Mass_Max_kgBpa = 0.2
DOCUMENT: Maximum permissable macrophyte biomass per unit area (carrying capacity).
- kilograms dry biomass per square meter

Mphy_Max_Gro_Const = 0.0025
DOCUMENT: Maximum growth rate constant for macrophyte growth.
- per hour

Mphy_Max_TP_gmPsm = Mphy_Mass_Max_kgBpa*Mphy_TP_gmPkgB

Mphy_Upt_fr_Sed_gmPsmhr = Mphy_Sed_Upt_Fract*Mphy_Total_TP_Uptake
DOCUMENT: Flux of TP uptake from sediment per unit area by macrophyte growth.
- grams TP per square meter per hour

Mphy_Root_Up_kghr = (Mphy_Upt_fr_Sed_gmPsmhr/1000)*Mphy_Habitat_Area

Mphy_Sed_Upt_Fract = 1-Mphy_Water_Upt_Fract

Mphy_Slough_Const = 0.0005
DOCUMENT: Rate constant for continuous sloughing of macrophytes based on an approximate turnover rate of macrophyte vegetation during the active growth season.
- 1/hours

Mphy_Slough_gmPsmhr = Mphy_Slough_Const*Mphy_Slough_Adj*(Mphy_TP_gmPsm - (Mphy_TP_Min_kgPpa*1000))
DOCUMENT: Flux of continous macrophyte TP sloughing per unit area.
- grams P per square meter per hour

Mphy_Total_TP_Uptake =
(Mphy_Max_Gro_Const*Mphy_TP_gmPsm*Mphy_Gro_Adj)
*((Mphy_Max_TP_gmPsm-Mphy_TP_gmPsm)/Mphy_Max_TP_gmPsm)
DOCUMENT: Total Macrophyte P areal uptake rate.
- grams TP per square meter per hour

Mphy_TP_gmPkgB = 3.2
DOCUMENT: Concentration of TP in macrophytes.
- grams P per kilogram dry biomass

Mphy_TP_gmPsm = (TP_Mphy_Mass_kg*1000)/Mphy_Habitat_Area

Mphy_T_Detach_kghr =
((Mphy_Erode_Slough_gmPsmhr+Mphy_Slough_gmPsmhr)/1000)*Mphy_Habitat_Area

Mphy_Water_Upt_Fract = 0.7
DOCUMENT: Fraction of the macrophyte uptake of soluble P that is removed from the water compartment through the leaves. The remaining fraction is taken up from the sediment through the roots.
- dimensionless

Mphy_W_Detach_kghr = Mphy_T_Detach_kghr*(1-Mphy_Detri_Fract)

Mphy_Upt_f_Water_gmPsmhr = Mphy_Total_TP_Uptake*Mphy_Water_Upt_Fract
DOCUMENT: Flux of TP uptake from water by macrophyte growth.
- grams TP per square meter per hour

Mphy__Leaf_Up_kghr = (Mphy_Upt_f_Water_gmPsmhr/1000)*Mphy_Habitat_Area

P Integration Module

PP_Water_Mass_kg(t) = PP_Water_Mass_kg(t - dt) + (PP_Inflow_kgphr +
TP_Pphy_W_Detach_kgphr + TP_Mphy_W_Detach__kgphr - PP_Outflow_kgphr -
TP_Detri_Settle_kgphr - TP_Pphy_W_Scav__kgphr) * dt

INIT PP_Water_Mass_kg = (PP_In_mgl/1000000)*(Volume_of_Water_cuft*28.316)
DOCUMENT: Mass of particulate phosphorus in the water volume contained within the reach.
- kilograms of P

INFLOWS:

PP_Inflow_kgphr = (PP_In_mgl/1000000)*(Q_In_cfs*28.316*60*60)+TP_Susload_In_kghr
DOCUMENT: Flux of particulate P entering the stream reach
- kilograms P per hour

TP_Pphy_W_Detach_kgphr = Perphy_W_Detach_kghr
DOCUMENT: Flux of TP in periphytic growth being sloughed and eroded (includes both the epilithon and epiphytes).
- kilograms TP per hour

TP_Mphy_W_Detach__kgphr = Mphy_W_Detach_kghr
DOCUMENT: Flux of Macrophyte TP that detaches and enters the particulate P compartment.
- kilograms TP per hour

OUTFLOWS:

PP_Outflow_kgphr =
PP_Water_Mass_kg*(1/(Volume_of_Water_cuft/(Outflow_cfs*60*60)))+TP_Susload_Out_kghr
DOCUMENT: Flux of particulate P leaving the reach.
- kilograms per hour

TP_Detri_Settle_kgphr = Settle_Fract_Const*PP_Water_Mass_kg
DOCUMENT: Flux of particulate P that settles into the detrital compartment
- kilograms per hour

TP_Pphy_W_Scav__kgphr = Epip_Scav_kghr
DOCUMENT: Flux of particulate P being removed by the "sticky" periphyton.
- kilograms TP per hour

SP_Mass_Water_kg(t) = SP_Mass_Water_kg(t - dt) + (SP_Inflow_kgphr +
SP_Sed_Desorb__kgphr + TP_Detri_Decay_kgphr + SP_Pphy_Leak_kgphr - SP_Outflow_kgphr
- SP_Sed_Adsorb_kgphr - SP_Mphy_Leaf_Up_kgphr - SP_Pphy_Uptake_kgphr) * dt

INIT SP_Mass_Water_kg = (SP_In_mgl/1000000)*(Volume_of_Water_cuft*28.316)
DOCUMENT: Mass of soluble P in the water volume contained within the reach.
- kilograms of P

INFLOWS:

SP_Inflow_kgphr = (SP_In_mgl/1000000)*(Q_In_cfs*28.316*60*60)
DOCUMENT: Flux of soluble P entering the reach.
- kilogramms P per hour

SP_Sed_Desorb__kgphr = SP_Desorb_kghr
DOCUMENT: Flux of soluble P being desorbed from the sediment compartment
- kilograms P per hour

TP_Detri_Decay_kgphr = Detri_TP_Decay_kghr
DOCUMENT: Flux of soluble P entering water compartment due to detrital decay
- kilograms P per hour

SP_Pphy_Leak_kgphr = Pphy_Leak_kghr
DOCUMENT: Flus of soluble P being "leaked" out of the periphyton
- kilograms P per hour

OUTFLOWS:

SP_Outflow_kgphr = SP_Mass_Water_kg*(1/(Volume_of_Water_cuft/(Outflow_cfs*60*60)))
DOCUMENT: Flux of soluble P leaving the reach
- kilograms P per hour

SP_Sed_Adsorb_kgphr = SP_Adsorb_kghr

SP_Mphy_Leaf_Up_kgphr = Mphy__Leaf_Up_kghr
DOCUMENT: Flux of soluble P being taken up by macrophyte growth
- kilograms P per hour

SP_Pphy_Uptake_kgphr = Pphy_Uptake_kghr
DOCUMENT: Flus of soluble P taken up by periphyton growth
- kilograms P per hour

TP_Detri_Mass_kg(t) = TP_Detri_Mass_kg(t - dt) + (TP_Mphy_D_Detach_kgphr + TP_Detri_Settle_kgphr - TP_Detri_Decay_kgphr - TP_Detri_Detach_kgphr) * dt

INIT TP_Detri_Mass_kg = Basal_Area_of_Reach*Detri_Mass_Init__kgpa
DOCUMENT: Mass of TP contained in the detritus that is within the reach.
- kilograms of P

INFLOWS:

TP_Mphy_D_Detach_kgphr = Mphy_D_Detach_kghr
DOCUMENT: Flux of macrophyte TP that is entering detrital compartment due to detachment.
- kilograms P per hour

TP_Detri_Settle_kgphr = Settle_Fract_Const*PP_Water_Mass_kg
DOCUMENT: Flux of particulate P that settles into the detrital compartment.
- kilograms per hour

OUTFLOWS:

TP_Detri_Decay_kgphr = Detri_TP_Decay_kghr
DOCUMENT: Flux of soluble P entering water compartment due to detrital decay.
- kilograms P per hour

TP_Detri_Detach_kgphr = Detri_Erode_kghr
DOCUMENT: Flux of Detrital TPleaving the reach.
- kilograms P per hour

TP_Mphy_Mass_kg(t) = TP_Mphy_Mass_kg(t - dt) + (TP_Mphy_Root_Up_kgphr + SP_Mphy_Leaf_Up_kgphr - TP_Mphy_D_Detach_kgphr - TP_Mphy_W_Detach__kgphr) * dt

INIT TP_Mphy_Mass_kg =
Mphy_Habitat_Area*Mphy_Mass_Init_kgBpa*Mphy_TP_gmPkgB/1000
DOCUMENT: Mass of phosphorus contained within the macrophyte compartment in the reach.
- kilograms of P

INFLOWS:

TP_Mphy_Root_Up_kgphr = Mphy_Root_Up_kghr
DOCUMENT: Flux of soluble P being taken up by macrophyte growth.
- kilograms P per hour

SP_Mphy_Leaf_Up_kgphr = Mphy__Leaf_Up_kghr
DOCUMENT: Flux of soluble P being taken up by macrophyte growth.
- kilograms P per hour

OUTFLOWS:

TP_Mphy_D_Detach_kgphr = Mphy_D_Detach_kghr
DOCUMENT: Flux of macrophyte TP that is entering detrital compartment due to detachment.

- kilograms P per hour

TP_Mphy_W_Detach__kgphr = Mphy_W_Detach_kghr
DOCUMENT: Flux of Macrophyte TP that detaches and enters the particulate P compartment.
- kilograms TP per hour

TP_Pphy_Mass_kg(t) = TP_Pphy_Mass_kg(t - dt) + (TP_Pphy_Sed_Scav__kgphr + SP_Pphy_Uptake_kgphr + TP_Pphy_W_Scav__kgphr - TP_Pphy_W_Detach_kgphr - SP_Pphy_Leak_kgphr - TP_Pphy_BL_Detach_kgphr) * dt

INIT TP_Pphy_Mass_kg = ((TP_Biom_mgPpa/1000000) +((Sed_gSpa/1000)*Act_Conc_Sed_P_gPkgS/1000))*Pphy_Habitat_Area
DOCUMENT: Mass of phosphorus contained in the periphyton communities (both epilithon plus epiphyton) within the reach.
- kilograms of P

INFLOWS:

TP_Pphy_Sed_Scav__kgphr = Epil_Scav_kgPhr

SP_Pphy_Uptake_kgphr = Pphy_Uptake_kghr
DOCUMENT: Flus of soluble P taken up by periphyton growth.
- kilograms P per hour

TP_Pphy_W_Scav__kgphr = Epip_Scav_kghr
DOCUMENT: Flux of particulate P being removed by the "sticky" periphyton.
- kilograms TP per hour

OUTFLOWS:

TP_Pphy_W_Detach_kgphr = Perphy_W_Detach_kghr
DOCUMENT: Flux of TP in periphytic growth being sloughed and eroded (includes both the epilithoin and epiphytes).
- kilograms TP per hour

SP_Pphy_Leak_kgphr = Pphy_Leak_kghr
DOCUMENT: Flus of soluble P being "leaked" out of the periphyton
- kilograms P per hour

TP_Pphy_BL_Detach_kgphr = Perphy_BL_Detach_kghr
TP_Sed_Mass_kg(t) = TP_Sed_Mass_kg(t - dt) + (SP_Sed_Adsorb_kgphr + TP_Bedload_In_kgphr - TP_BedLoad_Out_kgphr - SP_Sed_Desorb__kgphr - TP_Mphy_Root_Up_kgphr - TP_Pphy_Sed_Scav__kgphr) * dt

INIT TP_Sed_Mass_kg = Sediment_Mass_kg*(TP_Sed_Init_gPkgS/1000)
DOCUMENT: Mass of phosphorus contained in the sediment compartment in the stream reach.
- kilograms of P

INFLOWS:

SP_Sed_Adsorb_kgphr = SP_Adsorb_kghr

TP_Bedload_In_kgphr = TP_Bedload_In_kghr
DOCUMENT: Flux of TP in bedload entering the reach

- kilograms per hour

OUTFLOWS:

TP_BedLoad_Out_kgphr = TP_Bedload_Out_kghr-TP_Pphy_Sed_Scav__kgphr
DOCUMENT: Flux of TP in bedload leaving the reach.
- kilograms TP per hour

SP_Sed_Desorb__kgphr = SP_Desorb_kghr
DOCUMENT: Flux of soluble P being desorbed from the sediment compartment.
- kilograms P per hour

TP_Mphy_Root_Up_kgphr = Mphy_Root_Up_kghr
DOCUMENT: Flux of soluble P being taken up by macrophyte growth.
- kilograms P per hour

TP_Pphy_Sed_Scav__kgphr = Epil_Scav_kgPhr

Settle_Fract_Const = 0.005

SP_In_mgl = 0.10
DOCUMENT: Concentration of the soluble TP entering the reach.
- milligrams TP per liter

TP_Inflow_kghr = PP_Inflow_kgphr+SP_Inflow_kgphr

TP_Outflow_kgph = SP_Outflow_kgphr+PP_Outflow_kgphr

Periphyton

Algal_Mass_gBpa(t) = Algal_Mass_gBpa(t - dt) + (Algal_Growth - Algal_Erosion - Algal_Slough) * dt

INIT Algal_Mass_gBpa = Algal_Mass_Init_gBpa
DOCUMENT: Standing crop of algal biomass per unit area of habitat.
- grams of dry biomass per square meter

INFLOWS:

Algal_Growth = mu*Algal_Mass_gBpa*Algal_Feedback*Algal_Gro_Adj
DOCUMENT: Flux of dry algal biomass per unit area due to algal growth.
- grams dry biomass per square meter per hour

OUTFLOWS:

Algal_Erosion = Pphy_Erosion_Coeff*Algal_Mass_gBpa
*((Algal_Mass_gBpa-Algal_Mass_Min_gBpa)/Algal_Mass_gBpa)
DOCUMENT: Flux of dry algal biomass per unit area habitat that is eroded due to high flows.
- grams dry biomass per square meter per hour

Algal_Slough =
(Algal_Mass_gBpa)*Pphy_Slough_Const*((Algal_Mass_gBpa-Algal_Mass_Min_gBpa)

/Algal_Mass_gBpa)
DOCUMENT: Flux of dry algal biomass per unit area that is sloughing off continuously because of increasing thickness of biofilm.
- grams dry biomass per square meter per hour

Sed_gSpa(t) = Sed_gSpa(t - dt) + (SusSed_Scavange - Sed_Erode - Sed_Slough) * dt

INIT Sed_gSpa = Algal_Mass_gBpa*Mult_Factor
DOCUMENT: Mass of dry sediment per unit area of the stream bottom within the reach.
- grams of dry sediment per square meter

INFLOWS:

SusSed_Scavange = Min(Ep_S,0.9*PP_Outflow_kgphr)+Min(El_S,0.9*TP_Bedload_Out_kghr)
DOCUMENT: Flux of sediment taken up into the "sticky" periphyton per unit area.
- grams dry sediment per square meter per hour

OUTFLOWS:

Sed_Erode =
Pphy_Erosion_Coeff*Sed_gSpa*((Algal_Mass_gBpa-Algal_Mass_Min_gBpa)/Algal_Mass_gBpa)
DOCUMENT: Flux of sediment mass incorporated into periphyton per unit area eroded due to high flows.
- gram sediment per square meter per hour

Sed_Slough =
Pphy_Slough_Const*Sed_gSpa*((Algal_Mass_gBpa-Algal_Mass_Min_gBpa)/Algal_Mass_gBpa)
DOCUMENT: Flux of sediment that is incorporated into periphyton per unit area that is continuously sloughed off.
- grams dry sediment per square meter per hour

TP_Biom_mgPpa(t) = TP_Biom_mgPpa(t - dt) + (BAP_Uptake - Algal_TP_Erosion - Algal_TP_Slough - TP_Algal_Leak) * dt

INIT TP_Biom_mgPpa = TP_Algal_Init_mgPpgB*Algal_Mass_gBpa
DOCUMENT: Mass of phosphorus in algal biomass per unit area of habitat.
- milligrams P per square meter

INFLOWS:

BAP_Uptake = P_Up_Rate_mgPgBhr*Algal_Mass_gBpa*TP_Uptake_Feedback*Algal_Gro_Adj
DOCUMENT: Flux of Phosphorus uptake per unit area due to algal growth.
- mg P per square meter per hour

OUTFLOWS:

Algal_TP_Erosion = Algal_Erosion*TP_Algal_mgPgB
- milligrams TP per square meter per hour

Algal_TP_Slough = Algal_Slough*TP_Algal_mgPgB
- milligrams TP per square meter per hour

TP_Algal_Leak = IF(TP_Algal_mgPgB>TP_Algal_Min_mgPgB) THEN
Leak_Rate_Const*TP_Biom_mgPpa*((TP_Algal_mgPgB-TP_Algal_Min_mgPgB)

/TP_Algal_Min_mgPgB) ELSE 0

Algal_Feedback = (Algal_Mass_Max_gBpa-Algal_Mass_gBpa)/Algal_Mass_Max_gBpa

Algal_Mass_Max_gBpa = 100
DOCUMENT: Maximum amount of algal biomass per unit area that can exist (carrying capacity).

- grams dry biomass per square meter

BAP_conc = SP_Out_mgl*BAP_Fraction
DOCUMENT: Phosphorus concentration in reactor vessel.
- mg/L

BAP_Fraction = 0.1
DOCUMENT: Fraction of the soluble P that is assumed to be bioavailable for plant uptake.
- dimensionless

Basal_Area_of_Reach = Length_of_Reach_m*Width_@LowQ_m
DOCUMENT: length * low flow width of stream channel.
- square meters

El_S = Algal_Growth*Epil_Ratio*Mult_Factor

Epil_Habitat_Area = Basal_Area_of_Reach*Epil_Hab_Area_Fract

Epil_Hab_Area_Fract = 0.75
DOCUMENT: Fraction of basal area of reach that is designated as epilithon habitat.
- dimensionless

Epil_Ratio = Epil_Habitat_Area/Pphy_Habitat_Area

Epil_Scav_kgPhr = MIN(Epil_Scav_P_kghr,(0.9*TP_Bedload_Out_kghr))

Epil_Scav_P_kghr = Epil_Habitat_Area*(Sed_TP_Scavange/1000000)

Epip_Scav_kghr = MIN(Epip_Scav_P_kgha,(0.9*PP_Outflow_kgphr))

Epip_Scav_P_kgha = Mphy_Habitat_Area*(Sed_TP_Scavange/1000000)

Ep_S = Algal_Growth*Mphy_Ratio*Mult_Factor

Km_adj = Km_P*(TP_Algal_Min_mgPgB/TP_Algal_mgPgB)
DOCUMENT: Uptake half saturation constant adjusted by internal phosphorus concentration (Q).
- milligrams BAP per liter

Km_P = 0.05
DOCUMENT: Uptake half saturation contant (between 0.02 and 0.06 mgBAP/l)
- milligrams BAP per liter

Mphy_Ratio = Mphy_Habitat_Area/Pphy_Habitat_Area

mu = Algal_mu_max*(1-(TP_Algal_Min_mgPgB)/TP_Algal_mgPgB)
DOCUMENT: Algal growth rate as a function of internal phosphorus concentration.
- per hour

Mult_Factor = 0.36*(PerCent_Ash_Pphy/(100-PerCent_Ash_Pphy))
DOCUMENT: Multiplication factor adjusting for the fraction of ash in the periphyton dry mass.
- dimensionless

PerCent_Ash_Pphy = 80
DOCUMENT: Per Cent of dry mass of periphyton that is ash.
- dimensionless

Periphy_gSpa = Algal_Mass_gBpa+Sed_gSpa

Periphy_mgPgB = Perphy_TP_mgPpa/Periphy_gSpa

Perphy_BL_Detach_kghr = Epil_Ratio*Pphy_TP_Detach_kghr*Pphy_Detach_Fract

Perphy_TP_mgPpa = (TP_Pphy_Mass_kg*1000000)/Pphy_Habitat_Area

Perphy_W_Detach_kghr =
Mphy_Ratio*Pphy_TP_Detach_kghr+(1-(Pphy_Detach_Fract))*Perphy_BL_Detach_kghr

Pphy_Habitat_Area = Epil_Habitat_Area+Mphy_Habitat_Area

Pphy_Leak_kghr = Pphy_Habitat_Area*(TP_Algal_Leak/1000000)

Pphy_Sed_TP_mgpa = (Sed_gSpa/1000)*Act_Conc_Sed_P_gPkgS*1000

Pphy_Slough_Const = 0.0001
DOCUMENT: Periphyton continuous sloughing rate constant.
- per hour

Pphy_TP_Detach_kghr =
(Pphy_Habitat_Area)*((Sed_TP_Erode+Sed_TP_Slough+Algal_TP_Erosion+Algal_TP_
Slough)/1000000)

Pphy_Uptake_kghr = Pphy_Habitat_Area*(BAP_Uptake/1000000)

P_Up_Rate_mgPgBhr =
(P_rho_Max*(BAP_conc/(Km_adj+BAP_conc))*(Ks_05u/(Ks_05u
+(TP_Algal_mgPgB-TP_Algal_Min_mgPgB))))
DOCUMENT: Phosphorus uptake rate.
- mg P/gram biomass per hour

Sed_TP_Erode = Sed_Erode*Act_Conc_Sed_P_gPkgS
DOCUMENT: areal flux of sediment TP that is eroded by higher flows.
- milligrams TP per square meter per hour

Sed_TP_Slough = Sed_Slough*Act_Conc_Sed_P_gPkgS
DOCUMENT: areal Flux of Sediment TP sloughing.
- mg TP per square meter per hour

Shear_Velocity = Avg_Vel_mps/(2.5*LOGN((12*Depth_Flow_m)/(Sed_Part_Dia_mm/1000)))
- Meters /sec

TP_Algal_mgPgB = (TP_Biom_mgPpa)/Algal_Mass_gBpa
DOCUMENT: Internal phosphorus concentration.
- mg P/gram biomass

TP_Uptake_Feedback = (TP_Algal_Max_mgPgB-TP_Algal_mgPgB)/TP_Algal_Max_mgPgB

Pphy_Erosion_Coeff = GRAPH(Shear_Velocity)
(0.00, 0.00), (0.0125, 0.00), (0.025, 0.0025), (0.0375, 0.0325), (0.05, 0.0925), (0.0625, 0.338), (0.075, 0.408), (0.0875, 0.425), (0.1, 0.445), (0.113, 0.45), (0.125, 0.45), (0.138, 0.45), (0.15, 0.45), (0.163, 0.45), (0.175, 0.45), (0.188, 0.45), (0.2, 0.45)
DOCUMENT: Sloughing is induced by increase in stream flow as indicated by shear velocity. High shear velocities increases frictional shear forces away.
- shear velocity in meters per second
- Periphyton Erosion Coefficient is dimensionless

Season Adjust

Julian_Date(t) = Julian_Date(t - dt) + (Day_Accum - Day_Out) * dt

INIT Julian_Date = Day_of_Run_Start
DOCUMENT: Julian Date - day of the year assuming that 1 January equals day 1.

Day_Accum = 1/24
DOCUMENT: A counter that increments Julian date by 1 day evey 24 hours. (the algorithm 1/24 applies only when the model run is set on hours)

Day_Out = if (Julian_Date>365.97) then 365/dt else 0
DOCUMENT: A counter that causes the Julian Date to be reset to 0 when the Julian date reaches 365. NOTE: These values apply when dt = 0.5

Day_of_Run_Start = 152
DOCUMENT: Julian date on which you begin your simulation (this number can be any integer between 1 and 365)

Adsorb_Adj = GRAPH(Julian_Date)
(0.00, 0.7), (15.2, 0.7), (30.4, 0.7), (45.6, 0.7), (60.8, 0.72), (76.0, 0.74), (91.3, 0.77), (106, 0.875), (122, 0.93), (137, 0.985), (152, 1.00), (167, 1.00), (183, 1.00), (198, 1.00), (213, 1.00), (228, 1.00), (243, 1.00), (259, 0.98), (274, 0.9), (289, 0.8), (304, 0.74), (319, 0.7), (335, 0.7), (350, 0.7), (365, 0.7)
DOCUMENT: A factor that adjusts for the rate of adsorption and desorption over the annual cycle due to changes in water temperature
- dimensionless

Algal_Gro_Adj = GRAPH(Julian_Date)
(0.00, 0.02), (15.2, 0.02), (30.4, 0.025), (45.6, 0.05), (60.8, 0.1), (76.0, 0.25), (91.3, 0.5), (106, 0.7), (122, 0.85), (137, 0.95), (152, 1.00), (167, 1.00), (183, 1.00), (198, 1.00), (213, 1.00), (228, 1.00), (243, 1.00), (259, 0.95), (274, 0.85), (289, 0.7), (304, 0.5), (319, 0.25), (335, 0.14), (350, 0.055), (365, 0.02)
DOCUMENT: A factor that adjusts the rate of growth of the algae in the periphyton due to water temperature and light intensity variations over the annual cycle.
- dimensionless

Detri_Decay_Adj = GRAPH(Julian_Date)
(0.00, 0.1), (15.2, 0.1), (30.4, 0.1), (45.6, 0.1), (60.8, 0.1), (76.0, 0.1), (91.3, 0.2), (106, 0.86), (122, 1.00), (137, 1.00), (152, 1.00), (167, 1.00), (183, 1.00), (198, 1.00), (213, 1.00), (228, 1.00), (243, 1.00), (259, 0.79), (274, 0.4), (289, 0.19), (304, 0.1), (319, 0.1), (335, 0.1), (350, 0.1), (365, 0.1)
DOCUMENT: A factor that adjusts the detrital decay rate over the annual cycle due to changes in water temperature
- dimensionless

Mphy_Gro_Adj = GRAPH(Julian_Date)
(0.00, 0.00), (15.2, 0.00), (30.4, 0.00), (45.6, 0.00), (60.8, 0.00), (76.0, 0.00), (91.3, 0.00), (106, 0.035), (122, 0.095), (137, 0.795), (152, 0.965), (167, 1.00), (183, 1.00), (198, 1.00), (213, 1.00), (228, 1.00), (243, 0.00), (259, 0.00), (274, 0.00), (289, 0.00), (304, 0.00), (319, 0.00), (335, 0.00), (350, 0.00), (365, 0.00)
DOCUMENT: A factor that adjusts to growth rate of macrophytes over the seasonal cycle due to changes in water temperature and light intensities.
- dimensionless

Mphy_Slough_Adj = GRAPH(Julian_Date)
(0.00, 10.0), (15.2, 10.0), (30.4, 10.0), (45.6, 10.0), (60.8,10.0), (76.0, 8.00), (91.3, 4.00), (106, 2.00), (122, 1.00), (137, 1.00), (152, 1.00), (167, 1.00), (183, 1.00), (198, 1.00), (213, 1.00), (228, 2.00), (243, 4.00), (259, 8.00), (274, 10.0), (289, 10.0), (304, 10.0), (319, 10.0), (335, 10.0), (350, 10.0), (365, 10.0)
DOCUMENT: A factor that adjusts the sloughing and erosion rate of the macrophytes assuming that with senescence the resistance to sloughing and erosion is lessened.

- dimensionless

Adsorption/Desorption/Diffusion

Act_Conc_Sed_P_gPkgS = (TP_Sed_Mass_kg*1000)/Sediment_Mass_kg
DOCUMENT: Actual Concentration of TP in Sediment.
- g TP/kg Dry Sediment

Diff_BL_Thick_cm = 1
DOCUMENT: Thickness of the diffusional boundary layer between sediment where equilibrium pore water P concentration exists and where the P concentration of the overlying water is representative of the entire reach.
- centimeters

Pore_Water_Conc_mgl =
100/(((Ads_Max_Cap_Sed*Ads_Affin_K)/(Act_Conc_Sed_P_gPkgS*0.15))-Ads_Affin_K)

SP_Adsorb_kghr = if (SP_Out_mgl>=Pore_Water_Conc_mgl) then (Diff_Const*60*60)*(1/1000)*((SP_Out_mgl-Pore_Water_Conc_mgl)/Diff_BL_Thick_cm)*(1/1000000)*(Length_of_Reach_m*100*Width_@LowQ_m*100*Sed_Area_Fract)*Adsorb_Adj else 0
DOCUMENT: Flux of soluble P being adsorbed from the water by the sediment.
- kilograms P per hour

SP_Desorb_kghr = IF(Pore_Water_Conc_mgl>SP_Out_mgl) THEN (Diff_Const*60*60)*(1/1000)*((Pore_Water_Conc_mgl-SP_Out_mgl)/Diff_BL_Thick_cm)*(Length_of_Reach_m*100*Width_@LowQ_m*100*Sed_Area_Fract)*(1/1000000)*Adsorb_Adj ELSE 0

- kilograms P per hour

Sediment

Sediment_Mass_kg(t) = Sediment_Mass_kg(t - dt) + (Bedload_In_kg_p_hr + Susload_In_kg_p_hr - Bedload_Out_kg_p_hr - Susload_Out_kg_p_hr) * dt

INIT Sediment_Mass_kg = Init_Sediment_Mass_kg
DOCUMENT: Mass of sediment contained within the reach.
- kilograms of dry sediment

INFLOWS:

Bedload_In_kg_p_hr = Bedload_Flux_kghr
DOCUMENT: Flux of mass of bedload into the reach.
- kilograms dry sediment per hour

Susload_In_kg_p_hr = Susload_Flux_kghr
DOCUMENT: Flux of mass of suspended load (suspended sediment) entering the reach.
- kilograms of dry sediment per hour

OUTFLOWS:

Bedload_Out_kg_p_hr = IF (Sed_Depth_cm<=0.2) THEN 0 ELSE Bedload_In_kg_p_hr
DOCUMENT: Flux of mass of bedload out of the reach.
- kilograms dry sediment per hour

Susload_Out_kg_p_hr = IF (Sed_Depth_cm<=0.2) THEN 0 ELSE Susload_In_kg_p_hr
DOCUMENT: Fluxof dry mass of suspended sediment leaving the reach.
- kilograms dry sediment per hour

Bedload_Conc_mgl = IF (Unit_Stream_Power Wwc) THEN J*((Unit_Stream_Power/Fall_Vel)-WwcAdj_i)^K ELSE 0
DOCUMENT: Concentration of Total Bed Load Sediment - the concnetration of the sediment that comprises total bedload as (Yang and Stall 1976)
- kg dry sediment/1000000kg water - ppm

Bedload_Flux_kghr = (Bedload_Conc_mgl*1000*Q_In_cms*60*60)/1000000
DOCUMENT: Rate of Bedload Discharge - An estimate of the capacity of the stream reach to transport total bedload.
- kg dry weight sediment/hour

Crit_Dmls_Shear_Stress = 10^(Log_Crit_Shear_Stress)
DOCUMENT: Critical Dimensionless Shear Stress - the shear stress at the surface of the sediment bed at which erosion can occur.
- dimensionless

Crit_Part_Dia_mm = (13.7*Hyd_Rad_m*Chan_Slope)*1000
DOCUMENT: Critical Particle Diameter - The maximum sized particulate that can be picked up from the stream bottom and moved by the flowing water. Defined as the stream competence.
- diameter in millimeters

Crit_Tract_Force_i =

Crit_Dmls_Shear_Stress*(Wt_Den_Sed-Wt_Den_Water)*(Sed_Part_Dia_mm/1000)
DOCUMENT: Critical Tractive Force - the critical value of tractive force. When the actual tractive force is greater than this critical value sediment can be eroded from the channel bottom. This value is determined from Fig. 8-6 as per Dingman (1984).
- Newtons/square meter - N/sm

Dyn_Visc_Water = Kin__Visc__Water*Mass_Den_Water
DOCUMENT: Dynamic Viscosity of Water - 1.007*10^(-3) Nsm-2 @ 20 deg C
- Newton-seconds/square meter

Erosive_Nr = (Friction_Vel*(Sed_Part_Dia_mm/1000))/Kin__Visc__Water
DOCUMENT: Erosive Reynolds Number.
- dimensionless

Fall_Vel = 10^log_Fall_Vel

Friction_Vel = (Chan_Slope*Grav_Const*Hyd_Rad_m)^0.5
DOCUMENT: Shear of Friction Velocity
- m/s

Init_Sediment_Mass_kg =
(Sed_Init_Depth/100)*(Length_of_Reach_m*Width_@LowQ_m*Sed_Area_Fract)
*(Sed_Bulk_Den*1000)
DOCUMENT: The initial mass of sediment in the stream reach as calculated.
- kilograms

Init_TP_Mass_Sediment_kg = (Init_Sediment_Mass_kg*TP_Sed_Init_gPkgS)/1000

J = (272000)/((Particulate_Nr^0.286)*(Friction_Vel/Fall_Vel)^0.457)
DOCUMENT: J is an empirical factor defined by Yang and Stall (1976).
- dimensionless

K = 1.799-0.178*(LOGN(Particulate_Nr))-0.136*LOGN(Friction_Vel/Fall_Vel)
DOCUMENT: K is an empirical factor as defined by Yang and Stall (1976).
- dimensionless

Kin__Visc__Water = 1.007*10^(-6)
DOCUMENT: Kinematic viscosity of water - 1.007*10^(-6) m2/s at 20 deg C
- square meters per second

Log_Erosive_Nr = LOG10(Erosive_Nr)
DOCUMENT: Log value of the Erosive Reynolds Number.

Log_Sed_Dia = LOG10(Sed_Part_Dia_mm)

Mass_Den_Sed = 1000*Spec_Grav_Sed
DOCUMENT: Mass density of sediment - the dry mass density of the bed sediment particles.
- kg/cubic meter

Mass_Den_Water = 1000*Spec_Grav_Water
DOCUMENT: Mass density of water.
- kg/cubic meter

Mod_Erosive_Nr = IF(LOGN(Erosive_Nr) 0.138249) THEN 10 ELSE Erosive_Nr
DOCUMENT: Modified Erosive Reynolds Number - This is the operational value of the erosive Reynolds Number that is used in the calculations.
- dimensionless

Particulate_Nr = (Fall_Vel*(Sed_Part_Dia_mm/1000)*Mass_Den_Water)/Dyn_Visc_Water
DOCUMENT: Particulate Reynolds Number.
- dimensionless

Sed_Depth_cm =
(Sediment_Mass_kg)/(Sed_Area_Fract*(Sed_Bulk_Den/1000)*Length_of_Reach_m*10
0*Width_@LowQ_m*100)

Spec_Grav_Sed = 2.65
DOCUMENT: Specific gravity of the sediment particles .
- dimensionless

Spec_Grav_Water = 1
DOCUMENT: Specific gravity of the water.
-dimensionless

SS_C_Mid_Depth = IF(Sed_Part_Dia_mm>Crit_Part_Dia_mm)THEN(0)
ELSE((Bedload_Ref_Conc*(((Depth_Flow_m-0.5*Depth_Flow_m)/(0.5*Depth_Flow_m)
*((2*Sed_Part_Dia_mm*0.001)/Depth_Flow_m)))^Z_for_Med_Fall_Vel_i))*1000
DOCUMENT: Suspended Sediment Concentration at Mid depth of flow - estimated by equation 8-71 as per Dingman (1984).
- grams/cubic meter -mg/l

Susload_Avg_C_mgl = SS_C_Mid_Depth
DOCUMENT: Average Suspended Sediment Concentration - the average concentration of the sediment suspended in the flowing water resulting from bedload transport.
- grams/cubic meter - mg/l

Susload_Flux_kghr = (Q_In_cms*60*60*Susload_Avg_C_mgl)/1000
DOCUMENT: Instantaneous Suspended Solids Loading Rate - the instantaneous loading rate of suspended solids in the flowing water resulting from bedload transport.
- kg. dry weight sediment/hour

TP_Bedload_In_kghr = Bedload_In_kg_p_hr*(TP_Sed_Init_gPkgS/1000)*Wt_Fract_Fines

TP_Bedload_Out_kghr =
(Act_Conc_Sed_P_gPkgS/1000)*Bedload_Out_kg_p_hr*Wt_Fract_Fines

TP_Susload_In_kghr = (TP_Sed_Init_gPkgS/1000)*Susload_In_kg_p_hr*Wt_Fract_Fines

TP_Susload_Out_kghr =
(Act_Conc_Sed_P_gPkgS/1000)*Susload_Out_kg_p_hr*Wt_Fract_Fines

Unit_Stream_Power = Avg_Vel_mps*Chan_Slope
DOCUMENT: Unit Stream Power - the time rate of fall of the flowing water AND the time rate of head loss.
- meters/second -mps

Wt_Den_Sed = Spec_Grav_Sed*9800
DOCUMENT: Weight density of sediment particles - the dry weight density of the particles of bed sediment.
- Newtons/cubic meter

Wt_Den_Water = 9800*Spec_Grav_Water
DOCUMENT: Weight density of water .
- Newtons/cubic meter

Wt_Fract_Fines = 0.03
DOCUMENT: Weight Fraction of the particles in the stream bottom sediment that are silt size and smaller.
- dimensionless

Wwc = WwcAdj_i*Fall_Vel
DOCUMENT: Critical Stream Power - a threshold value of the unit stream power below which there is no sediment transport.
- meters/second

WwcAdj_i = IF(Erosive_Nr)70 THEN (((2.5/(0.434*LOGN(Mod_Erosive_Nr)-0.06))+0.66) *Chan_Slope) ELSE 2.05*Chan_Slope
DOCUMENT: Adj. Critical Unit Stream Power - a threshold value of the unit stream power below which there is no sediment transport. This equation accounts for different conditions of flow roughness as per Yang and Stall (1976).
- meters/second

Z_for_Med_Fall_Vel_i = Fall_Vel/(Friction_Vel*vonKarmen_Const)
DOCUMENT: The Z exponent - the value of the exponent Z for eqaution 8-71 Dingman (1984). Small values of Z (< than approx. 0.1 to 0.2) indicate a uniform distribution of sediment throughout the flow depth.
- dimensionless

Log_Crit_Shear_Stress = GRAPH(Log_Erosive_Nr)
(-2.00, -0.38), (-1.50, -0.515), (-1.00, -0.69), (-0.5, -0.824), (0.00, -1.09), (0.5, -1.48), (1.00, -1.66), (1.50, -1.37), (2.00, -1.30), (2.50, -1.30), (3.00, -1.30)
DOCUMENT: Relationship between log(erosive reynolds number) and log(critical dimensionless shear stress) from Figure 8.6 as per Dingman (1984).

log_Fall_Vel = GRAPH(Log_Sed_Dia)
(-2.00, -4.22), (-1.50, -3.00), (-1.00, -2.00), (-0.5, -1.30), (0.00, -0.699), (0.5, -0.522), (1.00, -0.347)

Stream Reach and Hydraulics

Avg_Vel_mps = Avg_Vel_vs_Q*0.3084
DOCUMENT: Average Flow Velocity (V) - Average velocity of water over the cross-section of flow.
- meters/second

cfs_to_cms = 0.02832
DOCUMENT: Conversion Factor - converts flow in cubic feet per second (CFS) to flow in cubic meters per second (CMS).

Depth_Flow_m = Depth_Flow_vs_Q*0.3084
DOCUMENT: Depth of Flow - the depth of the flowing water in the channel.
- meters

Detention_Time_hrs = Volume_of_Water_cuft/(Q_In_cfs*60*60)

Hyd_Rad_m = Hyd_Rad_vs_Q*0.3084
DOCUMENT: Hydraulic Radius (R) - Defined as the cross sectional area of flow/perimeter wetted by the flow.
- meters

Length_of_Reach_m = 150
DOCUMENT: Length of stream reach.
- meters

Outflow_cfs = Q_In_cfs

PP_Conc_Water_kgl = (PP_Water_Mass_kg)/(Volume_of_Water_cuft*28.316)
DOCUMENT: Concentration of Soluble P in Flowing Water Leaving the Reach
- kg/l

PP_In_mgl = TP_In_mgl-SP_In_mgl

PP_Out_mgl = PP_Conc_Water_kgl*1000000

Q_In_cfs = 6
DOCUMENT: Stream flow entering the reach.
- cubic feet per second

Q_In_cms = cfs_to_cms*Q_In_cfs
DOCUMENT: Stream discharge - the flow in the stream.
- cubic meters/second - cms

SP_Conc_Water_kgl = (SP_Mass_Water_kg)/(Volume_of_Water_cuft*28.316)
DOCUMENT: Concentration of Soluble P in Flowing Water Leaving the reach.
- mg/l

SP_Out_mgl = SP_Conc_Water_kgl*1000000

Time_Travel_hrs = Length_of_Reach_m/(Avg_Vel_mps*60*60)

TP_Conc_Water_mgl = PP_Out_mgl+SP_Out_mgl

TP_In_mgl = 0.14
DOCUMENT: Concetration of Total P entering stream reach.
- milligrams TP per liter

TP_Out_mgl = PP_Out_mgl+SP_Out_mgl

Volume_of_Water_cuft = XSArea_Flow_sf*Length_of_Reach_m*3.28

XSArea_Flow_sf = Q_In_cfs/Avg_Vel_vs_Q

Avg_Vel_vs_Q = GRAPH(Q_In_cfs)
(0.00, 0.00), (100, 2.60), (200, 3.10), (300, 3.50), (400, 3.90), (500, 4.30), (600, 4.50), (700, 4.80), (800, 5.00), (900, 5.20), (1000, 5.40), (1100, 5.60), (1200, 5.80), (1300, 5.90), (1400, 6.10), (1500, 6.20), (1600, 6.40), (1700, 6.50), (1800, 6.60), (1900, 6.80), (2000, 6.90), (2100, 7.00), (2200, 7.10), (2300, 7.20), (2400, 7.30), (2500, 7.30), (2600, 7.40), (2700, 7.50), (2800, 7.50), (2900, 7.60), (3000, 7.70), (3100, 7.80), (3200, 7.80), (3300, 7.90), (3400, 7.90), (3500, 7.90), (3600, 7.90), (3700, 7.90), (3800, 8.00), (3900, 8.00), (4000, 8.00), (4100, 8.10), (4200, 8.10), (4300, 8.10), (4400, 8.10), (4500, 8.20), (4600, 8.20), (4700, 8.30), (4800, 8.30), (4900, 8.30), (5000, 8.30), (5100, 8.40), (5200, 8.40), (5300, 8.40), (5400, 8.50), (5500, 8.50), (5600, 8.50), (5700, 8.60), (5800, 8.60), (5900, 8.60), (6000, 8.70), (6100, 8.70), (6200, 8.70), (6300, 8.80), (6400, 8.80), (6500, 8.90), (6600, 8.90), (6700, 8.90), (6800, 8.90), (6900, 9.00), (7000, 9.00), (7100, 9.00), (7200, 9.10), (7300, 9.10), (7400, 9.10), (7500, 9.20), (7600, 9.20), (7700, 9.20), (7800, 9.30), (7900, 9.30), (8000, 9.30), (8100, 9.40), (8200, 9.40), (8300, 9.40), (8400, 9.50), (8500, 9.50), (8600, 9.50), (8700, 9.50), (8800, 9.60), (8900, 9.60), (9000, 9.60), (9100, 9.60), (9200, 9.70), (9300, 9.70), (9400, 9.70), (9500, 9.70), (9600, 9.80), (9700, 9.80), (9800, 9.90), (9900, 9.90), (10000, 9.90)
DOCUMENT: Relationship between the Average velocity over the cross section of flow and streamflow as determined by the shape and dimensions of the cross section of the stream channel and flood plain.
- average velocity in meters per second
- streamflow in cubic feet per second

Depth_Flow_vs_Q = GRAPH(Q_In_cfs)
(0.00, 0.00), (100, 1.60), (200, 2.00), (300, 2.30), (400, 2.50), (500, 2.80), (600, 3.00), (700, 3.20), (800, 3.30), (900, 3.50), (1000, 3.70), (1100, 3.80), (1200, 3.90), (1300, 4.10), (1400, 4.20), (1500, 4.40), (1600, 4.50), (1700, 4.70), (1800, 4.70), (1900, 4.90), (2000, 5.00), (2100, 5.10), (2200, 5.20), (2300, 5.30), (2400, 5.40), (2500, 5.50), (2600, 5.60), (2700, 5.70), (2800, 5.80), (2900, 5.90), (3000, 6.00), (3100, 6.10), (3200, 6.20), (3300, 6.30), (3400, 6.30), (3500, 6.40), (3600, 6.50), (3700, 6.60), (3800, 6.60), (3900, 6.70), (4000, 6.70), (4100, 6.90), (4200, 6.90), (4300, 7.00), (4400, 7.10), (4500, 7.10), (4600, 7.20), (4700, 7.30), (4800, 7.40), (4900, 7.40), (5000, 7.50), (5100, 7.60), (5200, 7.60), (5300, 7.70), (5400, 7.70), (5500, 7.80), (5600, 7.90), (5700, 7.90), (5800, 8.00), (5900, 8.10), (6000, 8.10), (6100, 8.20), (6200, 8.20), (6300, 8.30), (6400, 8.40), (6500, 8.40), (6600, 8.50), (6700, 8.60), (6800, 8.60), (6900, 8.70), (7000, 8.70), (7100, 8.80), (7200, 8.80), (7300, 8.90), (7400, 8.90), (7500, 9.00), (7600, 9.00), (7700, 9.10), (7800, 9.10), (7900, 9.20), (8000, 9.30), (8100, 9.30), (8200, 9.40), (8300, 9.40), (8400, 9.40), (8500, 9.50), (8600, 9.50), (8700, 9.60), (8800, 9.70), (8900, 9.70), (9000, 9.70), (9100, 9.80), (9200, 9.80), (9300, 9.90), (9400, 9.90), (9500, 10.0), (9600, 10.1), (9700, 10.0), (9800, 10.1), (9900, 10.2), (10000, 10.2)
DOCUMENT: Relationship of Depth of Flow vs streamflow as determined by the shape and dimensions of the cross section of the stream channel and flood plain.
- depth of flow in meters
- streamflow in cubic feet per second

Hyd_Rad_vs_Q = GRAPH(Q_In_cfs)
(0.00, 0.00), (100, 0.8), (200, 1.00), (300, 1.30), (400, 1.40), (500, 1.60), (600, 1.80), (700, 2.00), (800, 2.10), (900, 2.20), (1000, 2.40), (1100, 2.50), (1200, 2.60), (1300, 2.70), (1400, 2.80), (1500, 2.90), (1600, 3.00), (1700, 3.10), (1800, 3.20), (1900, 3.30), (2000, 3.40), (2100, 3.40), (2200, 3.50), (2300, 3.40), (2400, 3.30), (2500, 3.30), (2600, 3.20), (2700, 3.20), (2800, 3.10), (2900, 3.10), (3000, 3.10), (3100, 3.00), (3200, 3.00), (3300, 3.00), (3400, 3.10), (3500, 3.10), (3600, 3.20), (3700, 3.30), (3800, 3.30), (3900, 3.40), (4000, 3.40), (4100, 3.50), (4200, 3.50), (4300, 3.60), (4400, 3.60), (4500, 3.70), (4600, 3.70),

(4700, 3.80), (4800, 3.80), (4900, 3.90), (5000, 3.90), (5100, 4.00), (5200, 4.00), (5300, 4.10), (5400, 4.20), (5500, 4.20), (5600, 4.30), (5700, 4.30), (5800, 4.40), (5900, 4.40), (6000, 4.50), (6100, 4.50), (6200, 4.60), (6300, 4.60), (6400, 4.70), (6500, 4.70), (6600, 4.80), (6700, 4.80), (6800, 4.80), (6900, 4.90), (7000, 5.00), (7100, 5.00), (7200, 5.00), (7300, 5.10), (7400, 5.10), (7500, 5.20), (7600, 5.20), (7700, 5.30), (7800, 5.30), (7900, 5.40), (8000, 5.40), (8100, 5.50), (8200, 5.50), (8300, 5.50), (8400, 5.60), (8500, 5.60), (8600, 5.70), (8700, 5.70), (8800, 5.70), (8900, 5.80), (9000, 5.80), (9100, 5.90), (9200, 5.90), (9300, 6.00), (9400, 6.00), (9500, 6.00), (9600, 6.10), (9700, 6.10), (9800, 6.10), (9900, 6.20), (10000, 6.20)
DOCUMENT: Relationship between hydraulic radius and streamflow as determined by the shape and dimensions of the cross section of the stream channel and flood plain.
- hydraulic radius in meters
- streamflow in cubic feet per second

Original STELLA graphs from simulations 1 through 3 (see Table 3.6.1.A for specific details of these simulations)

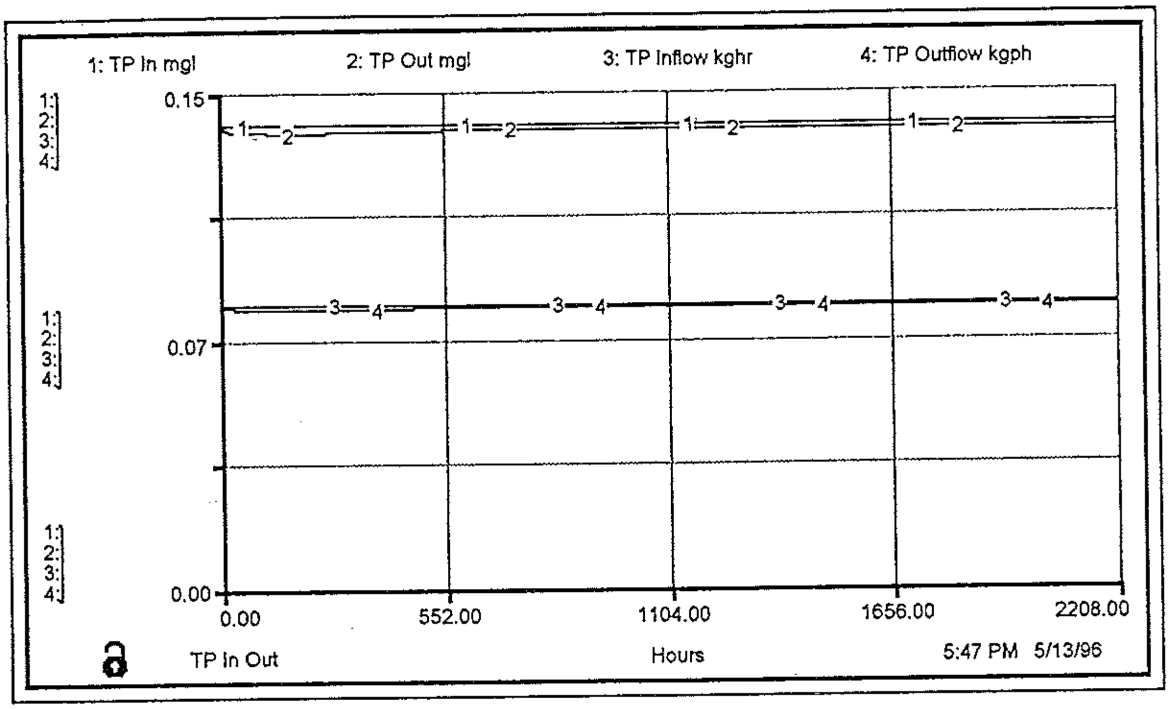


Figure 1: Simulation 1 (Spear St.) TP into and out of the reach as both concentration (curve 1 = in, curve 2 = out; mg/L) and flux (curve 3 = in, curve 4 = out; kg/hr).

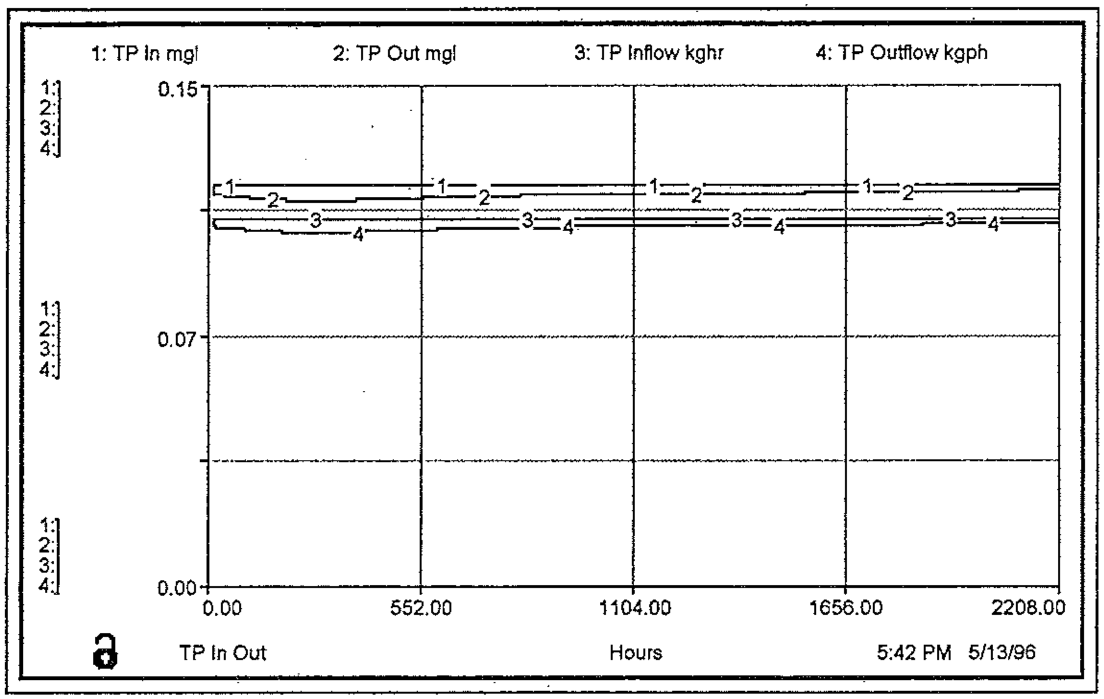


Figure 2: Simulation 2 (Bacon Dr.) TP into and out of the reach as both concentration (curve 1 = in, curve 2 = out; mg/L) and flux (curve 3 = in, curve 4 = out; kg/hr).

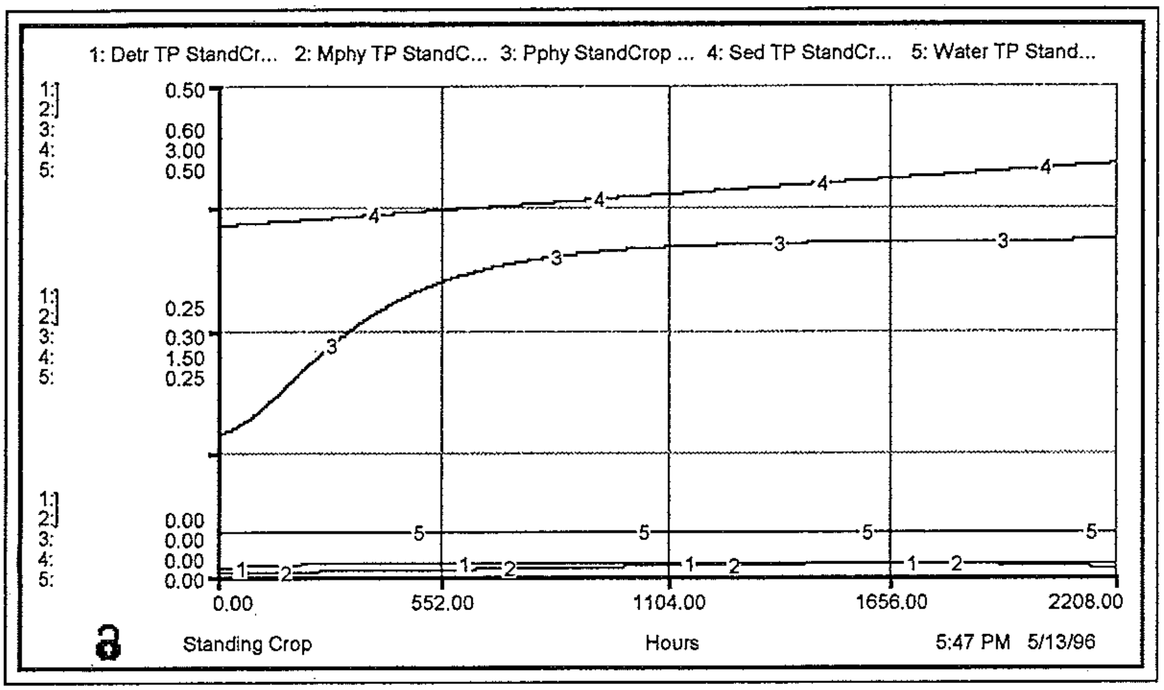


Figure 3. Simulation 1 (Spear St.) TP in all stocks (i.e. standing crops) as g TP/m^2 of stream reach (curve 1 = detritus; curve 2 = macrophytes; curve 3 = periphyton; curve 4 = sediment; curve 5 = water).

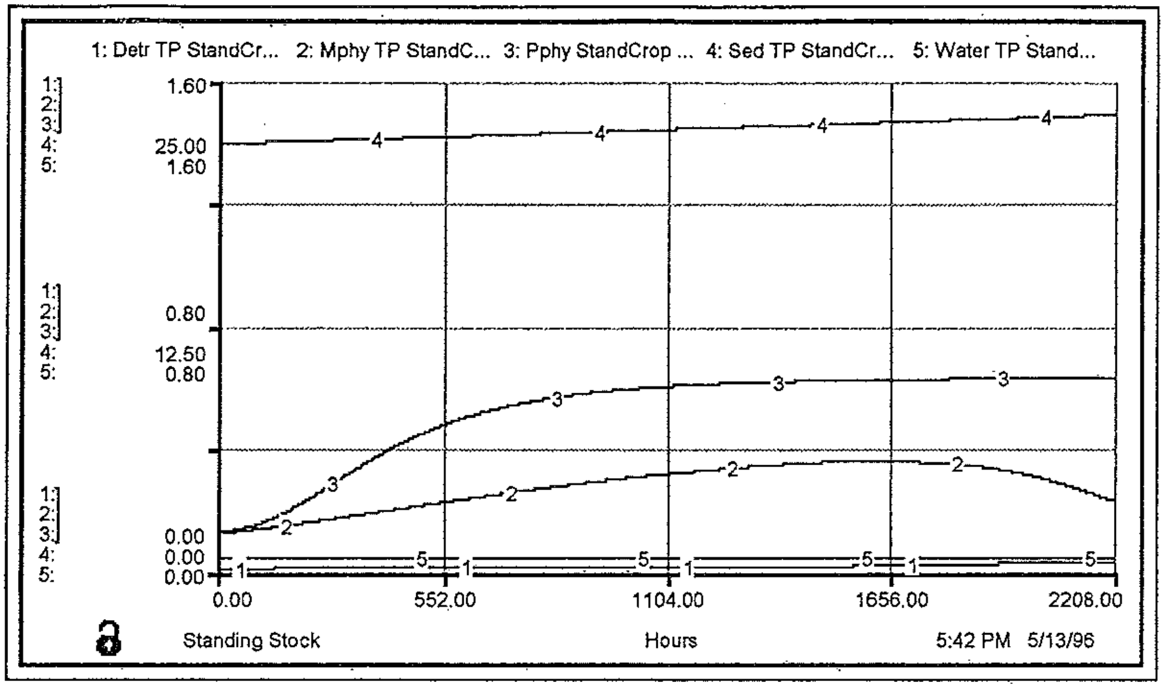


Figure 4. Simulation 2 (Bacon Dr.) TP in all stocks (i.e. standing crops) as g TP/m^2 of stream reach (curve 1 = detritus; curve 2 = macrophytes; curve 3 = periphyton; curve 4 = sediment; curve 5 = water).

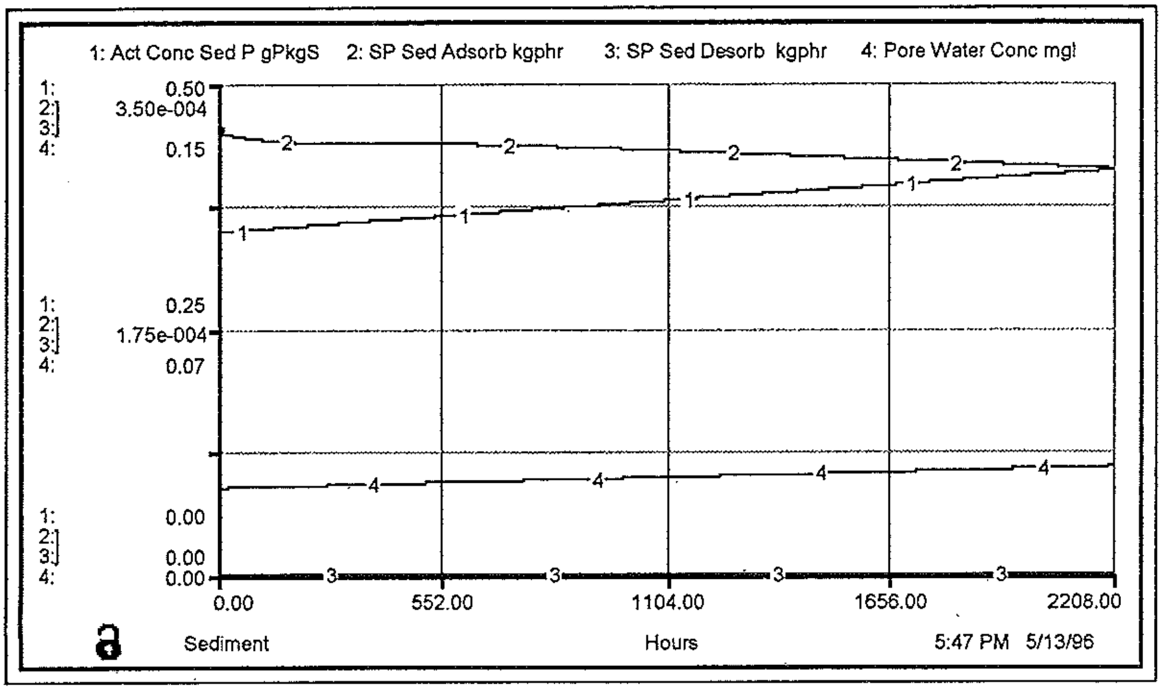


Figure 5. Simulation 1 (Spear St.) Phosphorus sediment relationships including sediment concentration (curve 1; g TP/kg sdeiment), adsorption rate of SP for total reach (curve 2; kg SP/hour) desorption rate of SP within the entire reach (curve 3; kg TP/hour) and pore water concentration (curve 4; mg SP/L).

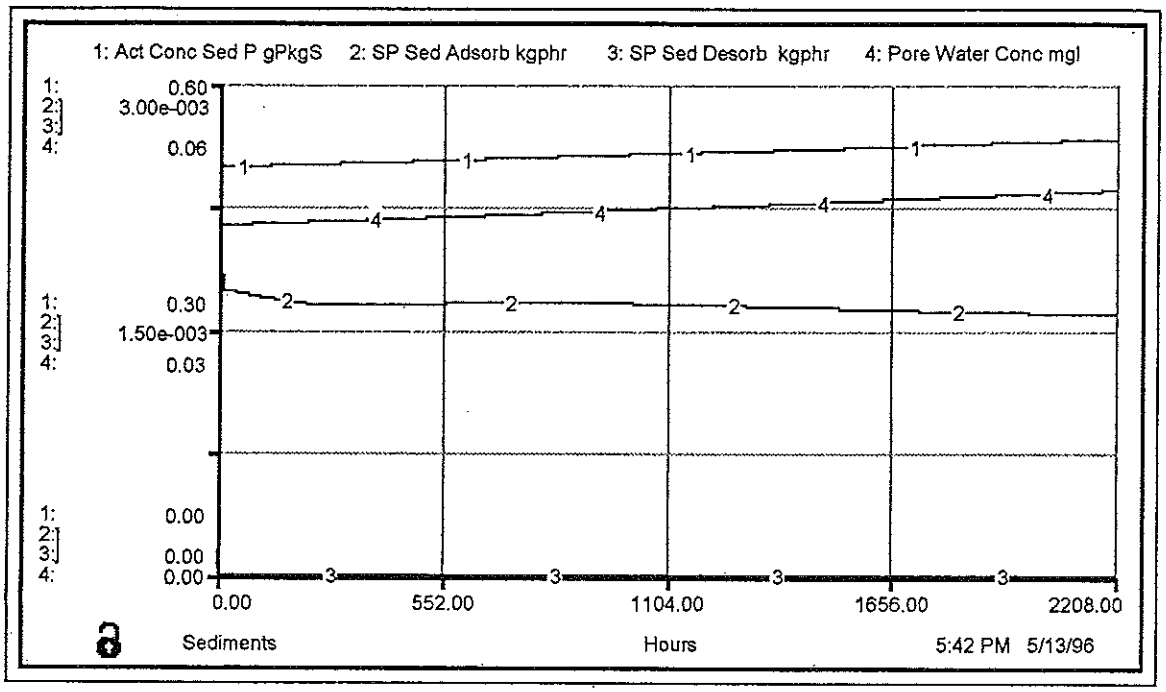


Figure 6. Simulation 2 (Bacon Dr.) Phosphorus sediment relationships including sediment concentration (curve 1; g TP/kg sdeiment), adsorption rate of SP for total reach (curve 2; kg SP/hour) desorption rate of SP within the entire reach (curve 3; kg TP/hour) and pore water concentration (curve 4; mg SP/L).

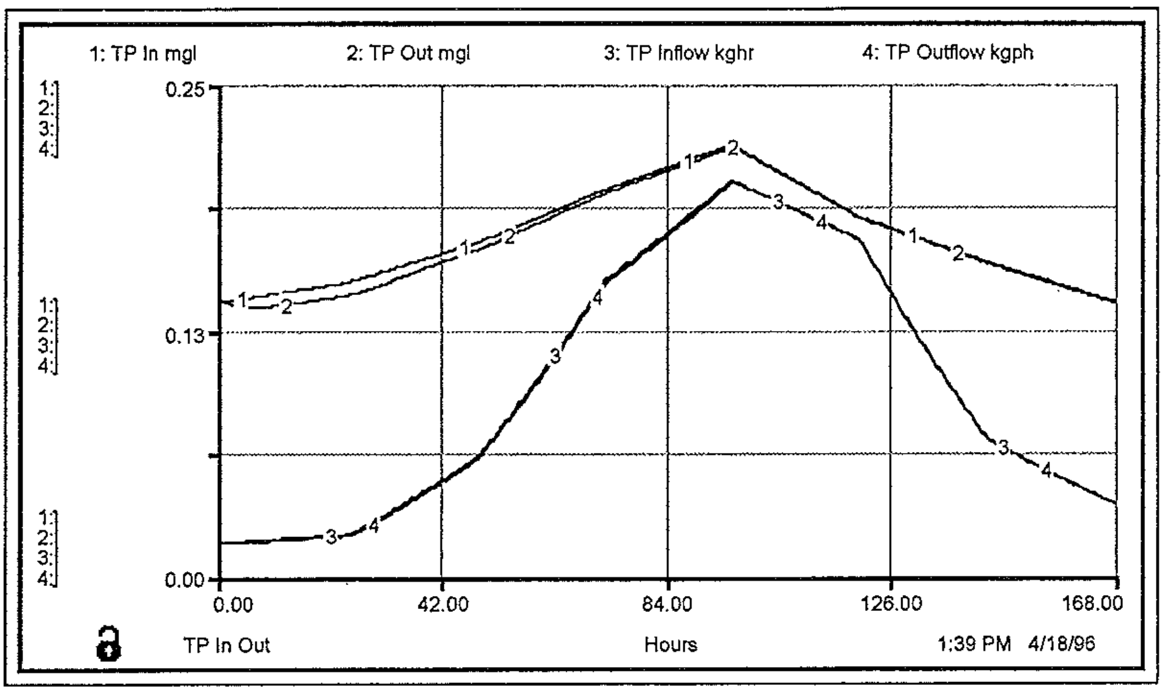


Figure 7. Simulation 3 (Spear St. summer storm) TP into and out of the reach as both concentration (curve 1 = in, curve 2 = out; mg/L) and flux (curve 3 = in, curve 4 = out; kg/hr).

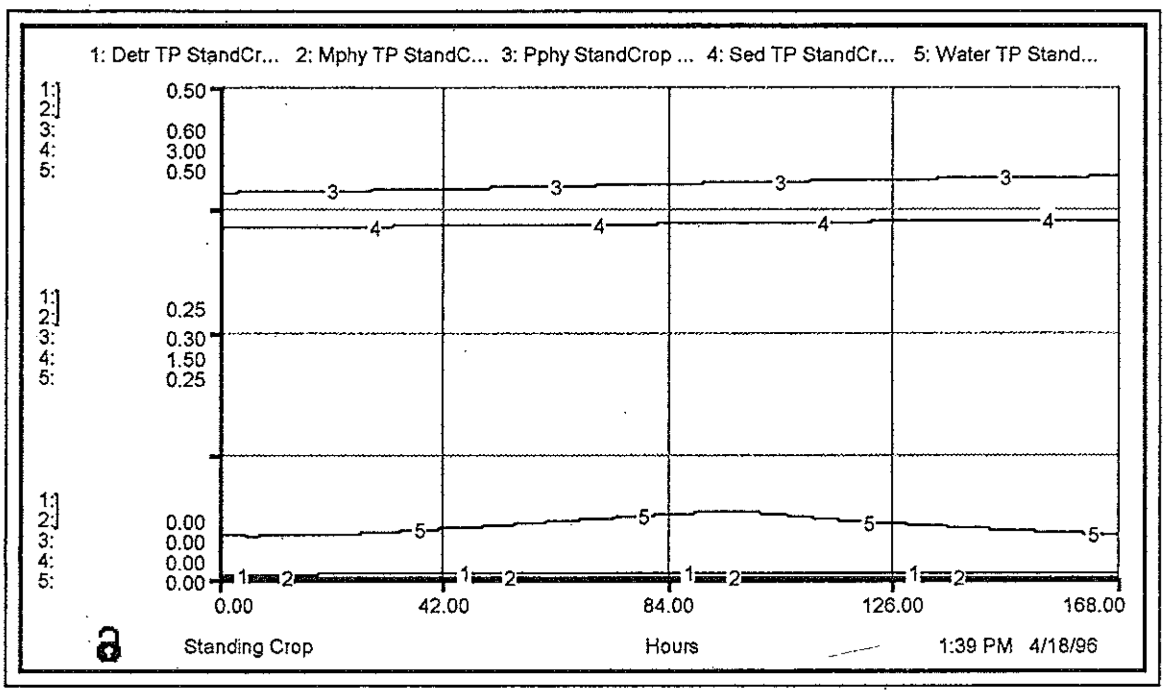


Figure 8. Simulation 3 (Spear St. summer storm) TP in all stocks (i.e. standing crops) as g TP/m^2 of stream reach (curve 1 = detritus; curve 2 = macrophytes; curve 3 = periphyton; curve 4 = sediment; curve 5 = water).

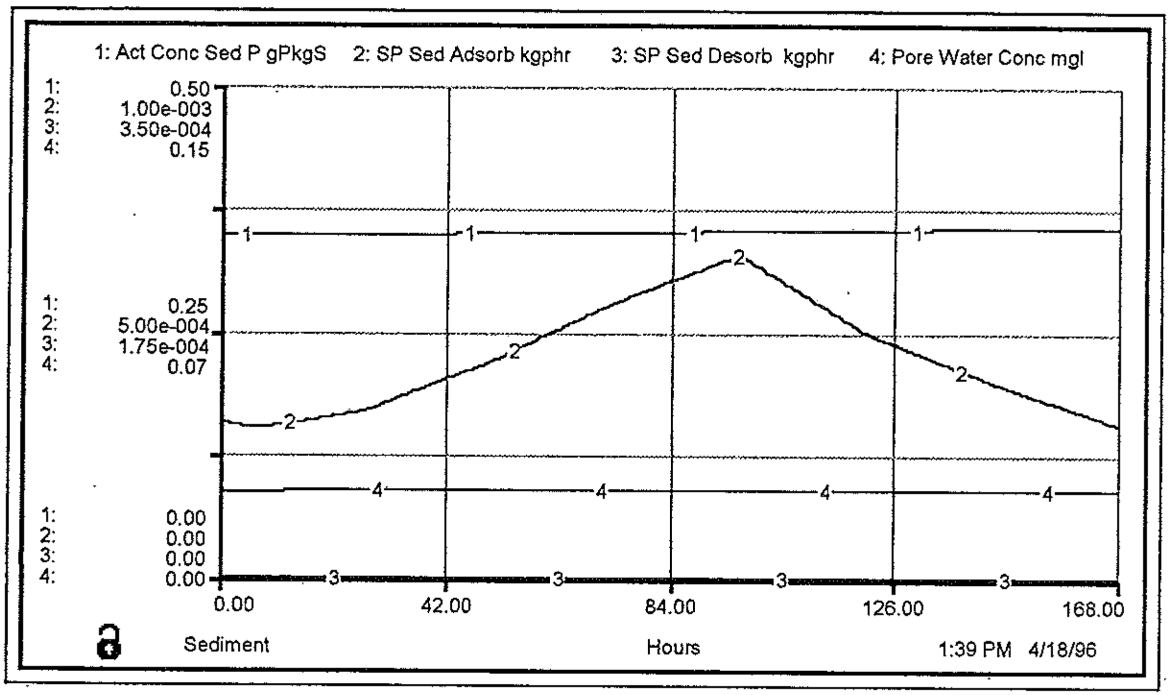


Figure 9. Simulation 3 (Spear St. summer storm) Phosphorus sediment relationships including sediment concentration (curve 1; g TP/kg sdeiment), adsorption rate of SP for total reach (curve 2; kg SP/hour) desorption rate of SP within the entire reach (curve 3; kg TP/hour) and pore water concentration (curve 4; mg SP/L).

APPENDIX C

Description of Stream Reach Characteristics

Two reaches of the LaPlatte River, the "Spear Streat" reach and the "Bacon Drive" reach, were selected for study in this project. In order to apply the DSPM to thee reaches it is necessary to characterize the stream channel hydraulics for each reach. The hydraulic characteristics of the stream have been defined through the use of simple field observations, stream cross-sections, and constructed maps of the reaches. This appendix will describe the hydraulics of the two study reaches as applicable to the DSPM modeling efforts described in this report.

Reach One - Spear Street

The Spear Street reach can be described as an armored riffle with approximately 75% of the stream channel bottom covered in gravel, cobbles and boulders. The remaining 25% of the channel is characterized by interstitial pockets of sand and gravel, with small fractions of silt and clay. Areal percentages of stream channel composition were determined from random point counts along the reach (Brown, personal communication 1995).

A series of cross-sections and associated stream corridor data for the LaPlatte River were provided by the USDA NRCS. Three of the data sets were located within the upper and lower limits established for the Spear Street reach. One of the three cross-sections was discarded because it was located directly under the Spear Street bridge, where the flood plain has been built up to support the overlying road. The remaining two cross-sections were similar in shape and dimension, and were therefore chosen to represent the entire reach (Figure C1). The hydraulic characteristics derived from these cross-sections were averaged together and used to drive the DSPM model. From the cross-sections, a low flow stream width of 37.5 ft, a bankfull width of 87.5 ft. and a bankfull flow depth is 7.0 ft were approximated (Table C1).

The NRCS data also provided stream channel slope measurements and estimates of roughness coefficients (n) for both the stream channel and the surrounding flood plains (Table C1). The Spear Street reach has an average stream channel slope of 0.0085 and an estimated n value of 0.045 (Table C1). The left and right floodplains have estimated n values of 0.065 and 0.085 respectively. The n values for this reach are consistent with those described by Chow (1964) for streams with rocky beds and some vegetaion along the banks.

The graphical relationships of depth of stream flow with both cross-sectional area and wetted perimeter were determined from the two cross-sections (Figure C2). A digitizing program which determines line lengths and polygon areas was used to determine cross-sectional area and wetted perimeter of both the floodplains and the stream channel. The wetted perimeter could easily be measured manually and the cross-sectional area could be determined with a planimeter or by plotting the cross-section on graph paper and counting blocks, if a digitizer were not available. Cross-sectional areas and wetted perimeters were measured at 0.5 ft depth intervals. The flow depth versus cross-sectional area and wetted perimeter, graphical relationships were later used as input to the Channel Hydraulic Model (CHM°) (Appendix-D) which is used to determine relationships of stream discharge with stream flow depth, stream velocity, and hydraulic radius.

Reach Two - Bacon Drive

The Bacon Drive reach is characterized by slow moving waters and a gentle slope (0.0025). This reach has an alluvial channel comprised of 57% gravel, 31% sand, and 12% silt and clay. Areal percentages of stream channel composition were determined from random sampling of the channel sediments, and a hand-lense grain size approximation (Brown, personal communication 1995).

Three of the NRCS cross-sections and data sets were located within the established boundaries of the Bacon Drive reach. Cross-sections 5-b and 5-c (Figure C3) were most characteristic of the general Bacon Drive stream corridor morphology and were therefore chosen to represent the entire reach. From the cross-sections, a low flow stream width of 45.0 ft, a bankfull width of 73.0 ft. and a bankfull flow depth is 6.0 ft were approximated (Table C1). The graphical relationship of depth of stream flow with both cross-sectional area and wetted perimeter (Figure C2) were also determined for later input to the CHM° model (Section D of this appendix).

The SCS approximated an n value of 0.033 (Table C1) for the Bacon Drive stream channel, which is consistent with values suggested by Chow (1964) for an alluvial, lower regime, channel. The left and right floodplains had estimated n values of 0.035 and 0.060 respectively (Table C1). These n values are much lower than those approximated for the Spear St. reach indicating an agricultural floodplain with little vegetation.

Table C-1. Hydraulic parameters for Spear St. and Bacon Dr. study reaches.

	Spear Street	Bacon Drive
Low Flow Stream Width (ft)	37.5	45.0
Bankfull Stream Width (ft)	87.5	73.0
Bankfull Flow Depth (ft)	7.0	6.0
Channel Roughness (n)	0.045	0.033
Left Floodplain n	0.065	0.035
Right Floodplain n	0.085	0.06
Slope (ft/ft)	0.0085	0.0025

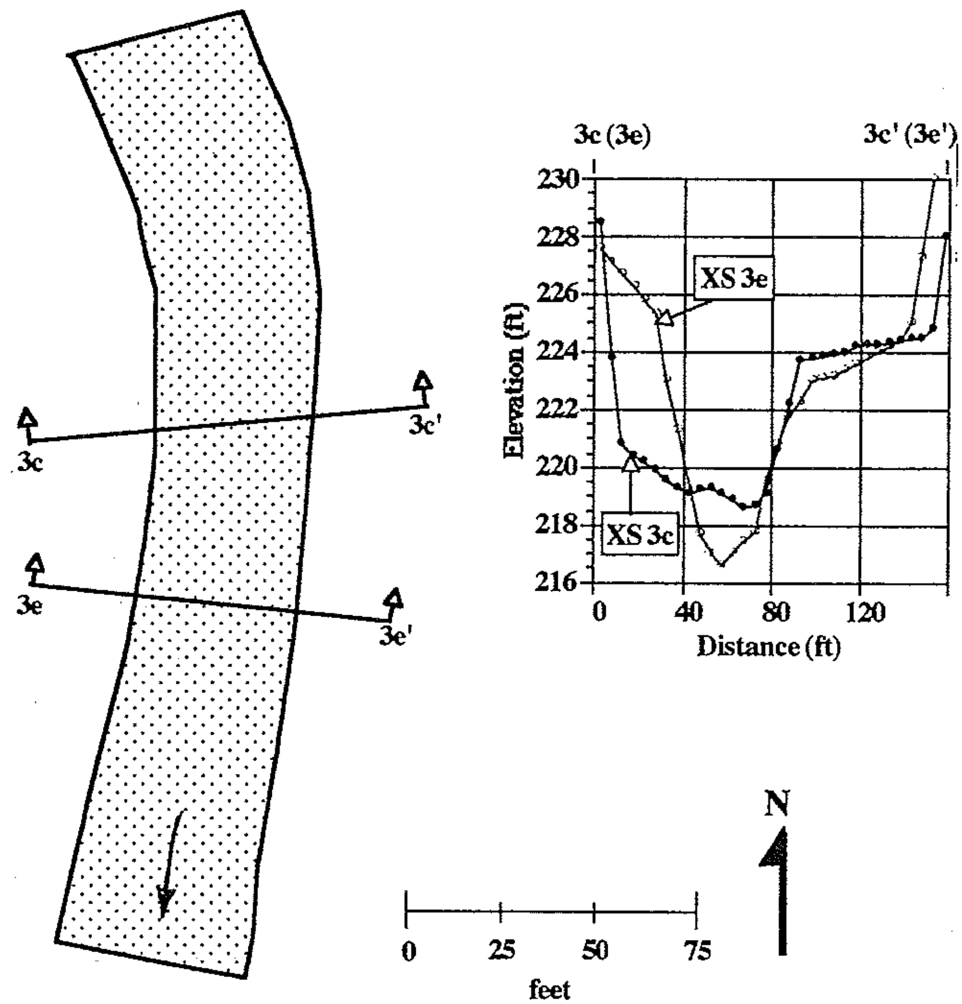
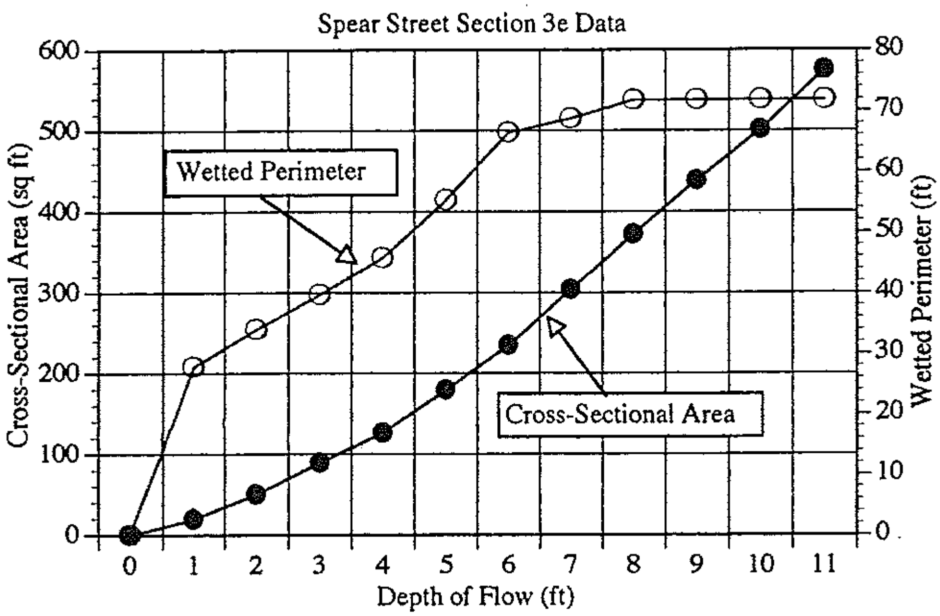


Figure C-1. Schematic map and SCS cross sections for Spear St. reach, LaPlatte River.



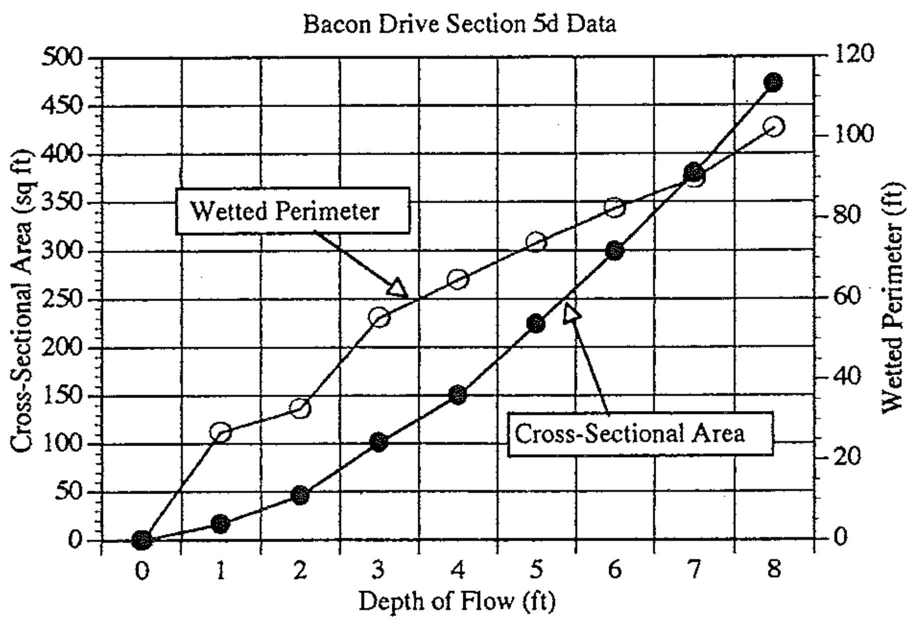


Figure C-2. Graphical relationships of flow depth with cross-sectional area and wetted perimeter for Spear St. section 3e (top) and Bacon Dr. section 5d (bottom).

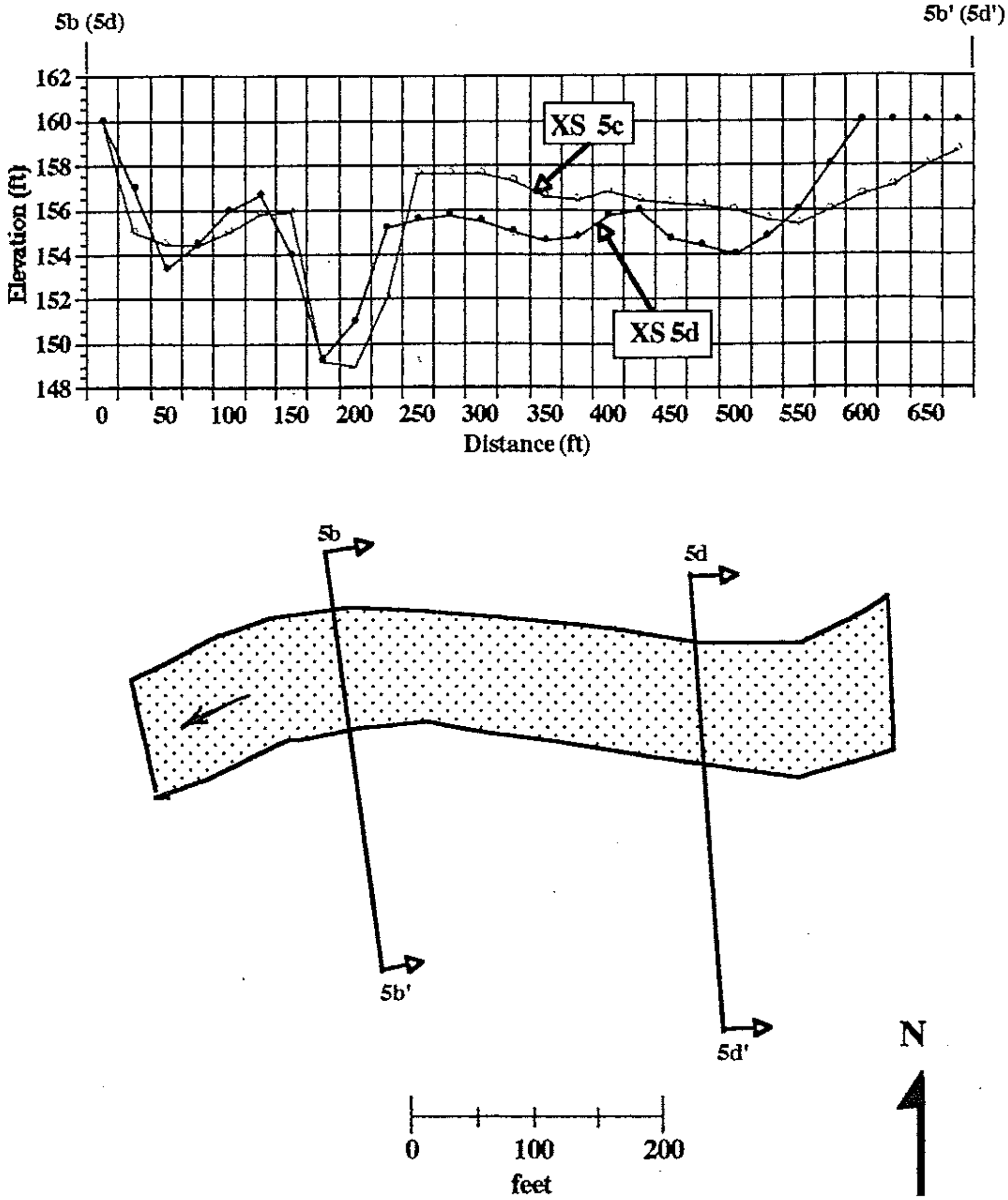


Figure C-3. Schematic map and SCS cross sections for Bacon Dr. reach, LaPlatte River.

APPENDIX D

Stream Reach Hydraulics

Description of DSPM Hydraulic Inputs

The DSPM requires the input of stream hydraulic parameters which control the relationships between stream flow and the cycling of both dissolved and particulate forms of P. These hydraulic parameters determine sediment and detritus transport as well as macrophyte and periphyton sloughing. The required hydraulic inputs to the DSPM for each reach are length, slope, low flow width, and the graphical relationships of stream discharge (Q cfs) with depth of flow (m), average stream velocity (ms^{-1}), and hydraulic radius (m). This appendix describes the methods used to determine the stream channel hydraulics of two reaches of the LaPlatte River.

A series of LaPlatte River cross-sections were provided by the USDA Vermont NRCS, from which two cross-sections for each study reach were chosen. These cross-sections were used to determine the hydraulic parameters of the stream. Section C of this appendix describes the methods used to estimate the reach length and low flow stream width, needed for the DSPM. Section C of the appendix also describes estimations of channel and floodplain roughness coefficients (n), channel slope, and the graphical relationships of depth of stream flow with both cross-sectional area and wetted perimeter, which are used as inputs to the Channel Hydraulic Model (CHM°). The CHM° model is used to develop the graphical relationship between stream discharge and depth of flow, average stream velocity, and hydraulic radius.

<u>The Channel Hydraulic Model (The CHM° Model)</u>

<u>Model Description</u> The Channel Hydraulic Model (CHM°) allows the user to define the hydraulic characteristics of the stream flow corridor (including both the stream channel and the flood plain areas) according to the Manning equation. The CHM° model, as developed by Cassell et al. 1995, is used within the dynamic simulation environment provided by the STELLA II® software (High Performance Systems 1992).

The Manning equation states that:

$$Q = (1.49/n)\ A\ R^{2/3}\ S^{1/2}$$

where:

Q = Volumetric flow rate
n = Manning's roughness coefficient
A = Cross sectional area of flow
R = Hydraulic radius (A/WP)
WP = Wetted perimeter
S = Slope of the stream channel

The CHM° model incorporates the analytical equations that define the open channel flow relationships of cross-sectional area of flow, hydraulic radius, width of flooding, average cross-sectional velocity and flow rates as related to varying flow depths for the stream reach. In the CHM° model, the cross-sectional area of the stream flow reach may be divided into as many as three sections: (1) the stream channel, (2) the left flood plain area and (3) the right flood plain area. When depths of flow exceed the specified bank-full depth of the stream channel the stream flow then begins to flow through the flood plain areas. Each section of the reach is characterized by its unique roughness coefficient, cross-sectional shape and dimensions. The cross-sectional area of flow, hydraulic radius, average velocity of flow, flow rates and width of flooding are then computed separately for each portion of the cross-section and then recalculated to give average values for the entire area of flow. These averages are input data for the DSPM hydrologic routines. The output from the CHM° models are cross-sectional area of flow, depth of flow, hydraulic radius, width of flooding, average cross-sectional velocity and flow rate. Figure D1 shows an overview of the structural diagram for the CHM° model.

<u>CHM° Model Inputs</u> All input data are entered into the screen objects contained within the **Data Inputs** sector. The data inputs are:

<u>Channel</u>

slope
roughness (n)
flow depth vs cross sectional area graphical relationship
flow depth vs wetted perimeter graphical relationship

<u>Left Floodplain</u>

roughness (n)
flow depth vs cross sectional area graphical relationship
flow depth vs wetted perimeter graphical relationship

Right Floodplain

roughness (n)
flow depth vs cross sectional area graphical relationship
flow depth vs wetted perimeter graphical relationship

Section C of this appendix details the collection of the necessary input data.

CHM° Model Outputs and Data Transformation Operations Within the **Model Outputs** sector are the screen objects that contain the various graphical and tabular outputs of the CHM° model, including cross-sectional area of flow, hydraulic radius, width of flooding, average cross-sectional velocity, and flow rate as a function of depth of flow. The **Flood Plain Outputs** sector contains the algorithms that compute the hydraulic characteristics for the cross-sections of left and right flood plains while the **Main Channel Outputs** sector contains algorithms that compute the hydraulics for the cross-section of the main channel. The total width of flooding, total flow rate and average cross-sectional velocity are computed in the **Overall Corridor Outputs** sector, and the total cross sectional area of flow is estimated in the **Corridor Cross-Section** sector.

For this study, only the tabular outputs of depth of flow, hydraulic radius, average cross-sectional velocity and flow rate are used to develop hydraulic input parameters for the DSPM. It should be noted, that the model output from any simulation model is rarely in equal increments, however, the DSPM requires the input of data based on equal increments of flow. Therefore, tabular output from the CHM° model were exported to an Excel 4 (Microsoft 1992) spreadsheet in which the data were manually transformed to format required by the DSPM.

These data transformation operations required the manual transformation of depth of flow, hydraulic radius, and average cross-sectional velocity data from unequal to equal increments of flow. The data are imported into an Excel 4 (Microsoft 1992) spreadsheet, and plots of flow versus depth of flow, hydraulic radius, and average cross-sectional velocity are created (Figure D2). The graphical relationships, in equal increments of flow, are then manually determined from the plots and input into the DSPM. In order for the DSPM to be sensitive to moderate changes in stream flow, a minimum of 100 cfs flow increments were necessary from 0.0 to 1.0×10^4 cfs. Smaller increments may be necessary for better resolution of hydrological changes during small flow events or for smaller fluvial systems.

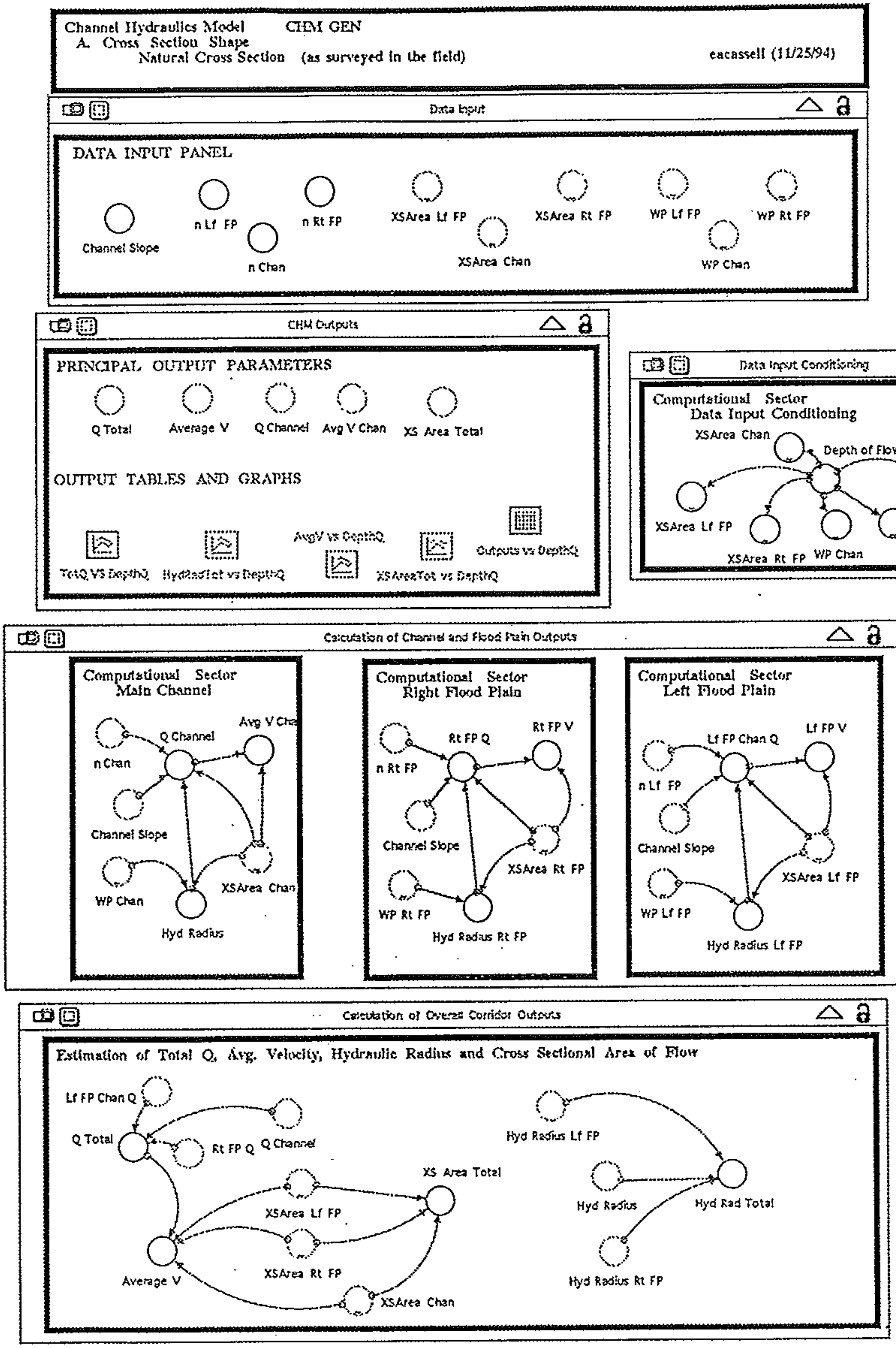


Figure D1 Structural Diagram of CHM Model

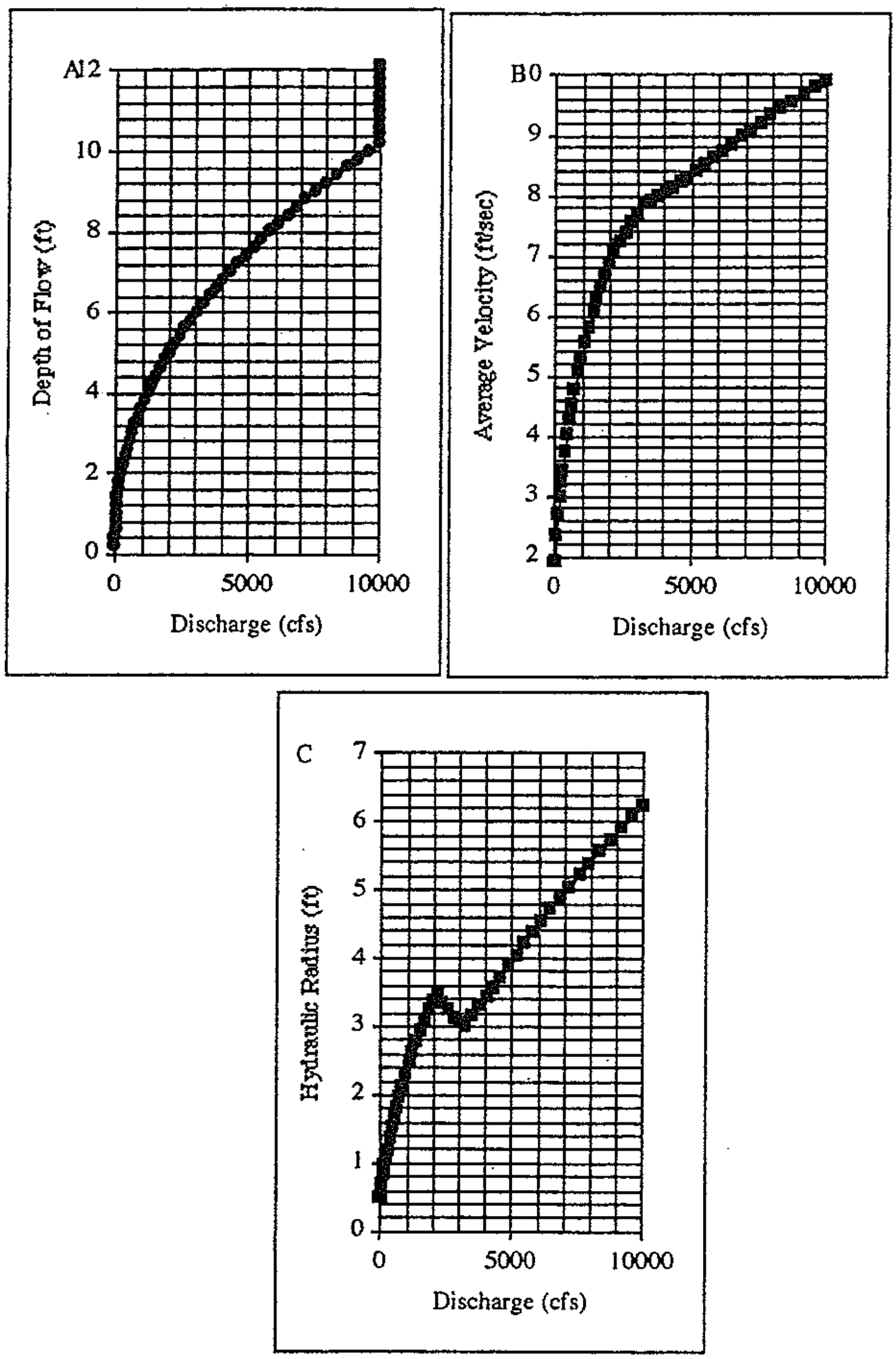


Figure D-2. Graphical relationships of discharge with Depth of Flow (A), Average Velocity (B), and Hydraulic Radius (C). Values of depth, velocity and hydraulic radius are estimated from plots in equal increments of discharge.